(12)

AD A138849

TR-191

COGNITIVE SIMULATION OF AN ANTI-SUBMARINE
WARFARE COMMANDER'S TACTICAL DECISION PROCESS

Contract Number N00014-81-C-0740

ALPHATECH, INC.
2 BURLINGTON EXECUTIVE CENTER
111 MIDDLESEX TURNPIKE
BURLINGTON, MA 01803
617-273-3388

ALPHATECH, INC.

TR-191

COGNITIVE SIMULATION OF AN ANTI-SUBMARINE
WARFARE COMMANDER'S TACTICAL DECISION PROCESS

Contract Number N00014-81-C-0740

By

M.G. Alexandridis
E.E. Entin
J.G. Wohl
J.C. Deckert

February 1984

Submitted to:

Mr. Gerald Malecki
Engineering Psychology Programs
Code 442
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

Work Unit Number:

NR460-001

ALPHATECH, Inc.
2 Burlington Executive Center
111 Middlesex Turnpike
Burlington, Massachusetts 01803
(617) 273-3388

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD A138849
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Cognitive Simulation of an Anti-Submarine Warfare Commander's Tactical Decision Process	5. TYPE OF REPORT & PERIOD COVERED Technical Report Sept. 1982 through Aug. 1983
	6. PERFORMING ORG. REPORT NUMBER TR-191
7. AUTHOR(s) M.G. Alexandridis, E.E. Entin, J.G. Wohl, J.C. Deckert	8. CONTRACT OR GRANT NUMBER(s) N00014-81-C-0740
9. PERFORMING ORGANIZATION NAME AND ADDRESS ALPHATECH, Inc. 111 Middlesex Turnpike Burlington, MA 01803	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR460-001
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research 800 North Quincy Street Arlington, VA 22217	12. REPORT DATE February 1984
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Decision making, cognitive modeling, anti-submarine warfare, probabilistic information processing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A normative-descriptive simulation model of an ASWC's tactical decision process is discussed. The decision process is conceptualized as a cascading of two cognitive activities: situation assessment and resource allocation. The ASWC model is driven by an environmental simulator, which updates the state of own-force platforms and enemy submarines and generates the submarine contacts from own-force sensors. On the basis of this information, the ASWC: (1) performs the multi-source/multi-sensor data correlation problem (situation

DD FORM 1 JAN 73 1473

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

assessment) and (2) allocates ASW aircraft for contact prosecution or target localization (resource management).

The normative representations used to describe the ASWC's cognitive activities are drawn from the detection, estimation, and statistical decision theories. The descriptive limitations, which have been used to constrain the normative models to produce human-like behavior, are drawn from the cognitive and behavioral literature. The limitations that are encoded explicitly into the model are: (1) short-term memory, (2) imperfect probabilistic information processing, and (3) threat-sensitive choice making.

The model outputs the sequence of aircraft allocation decisions made by the ASWC and computes two measures of ASW system effectiveness: The number of submarines successfully brought to attack criterion and the mean time-to-engagement.

A hypothetical case study is presented to demonstrate the model. Sensitivity analyses on both cognitive and operational parameters are discussed to illustrate the potential applications of a fully validated cognitive simulation model.

A-1

ABSTRACT

A normative-descriptive simulation model of an ASWC's tactical decision process is discussed. The decision process is conceptualized as a cascading of two cognitive activities: situation assessment and resource allocation. The ASWC model is driven by an environmental simulator, which updates the state of own-force platforms and enemy submarines and generates the submarine contacts from own-force sensors. On the basis of this information, the ASWC: (1) performs the multi-source/multi-sensor data correlation problem (situation assessment) and (2) allocates ASW aircraft for contact prosecution or target localization (resource management).

The normative representations used to describe the ASWC's cognitive activities are drawn from the detection, estimation, and statistical decision theories. The descriptive limitations, which have been used to constrain the normative models to produce human-like behavior, are drawn from the cognitive and behavioral literature. The limitations that are encoded explicitly into the model are: (1) short-term memory, (2) imperfect probabilistic information processing, and (3) threat-sensitive choice making.

The model outputs the sequence of aircraft allocation decisions made by the ASWC and computes two measures of ASW system effectiveness: The number of submarines successfully brought to attack criterion and the mean time-to-engagement.

A hypothetical case study is presented to demonstrate the model. Sensitivity analyses on both cognitive and operational parameters are discussed to illustrate the potential applications of a fully validated cognitive simulation model.

CONTENTS

CONTENTS (continued)

FIGURES

FIGURES (continued)

TABLES

ACKNOWLEDGEMENT

The authors would like to acknowledge the contributions of Prof. Frank Snyder at the Naval War College, and Cmdr. Steven O'Keefe at the Surface Warfare Officer's School in Newport, R.I. They graciously provided much information on anti-submarine warfare; however, they are not responsible fr the contents of this report.

SECTION 1

INTRODUCTION

To evaluate and to predict accurately the overall performance of a large-scale man-machine system, it is necessary to develop functional mathematical representations of both the human and the machine subsystems as well as the interface through which they interact (Wymore, 1967). However, until recently it has only been possible to model successfully humans that perform manual control tasks, i.e., data keypunching, button depressing, or manual tracking (Kleinman et al., 1971; Sheridan and Ferrell, 1974; Rouse et al., 1983). Humans performing more cognitively oriented tasks have been either ignored or have been inaccurately represented by nodes that perform optimally with an arbitrary decision time delay. The credibility of the results rendered by simulations employing these primitive approaches to human decision modeling is diminishing rapidly. The continuing introduction of new electronic technology into the military has, to quote Slovic (1982, p. 157),

> ...changed radically the hierarchy of needed human skills. Strength and motor performance have become less important. So have perceptual skills although these will never be unimportant. Intellectual skills, especially those of judgment and decision making have become the crucial human elements.

The motivations for constructing cognitive models of human decision tasks are fourfold. First, they can be used to replace the primitive representations of human decision makers currently found in large-scale military simulations. In this role, the simulations can be used as aids to command and

control system design and evaluation and to relieve the labor intensiveness of war games. Second, such models can be used to determine the relative importance of selected operational variables and their relationships, as a preliminary to tactical decision aid and display design. It is significant to note that while all three services have funded development of computerized tactical decision aids, there appear to be major psychological obstacles to their acceptance for operational use; by 1981, few if any such aids had actually found their way into the field (Sinaiko, 1977; Wohl, 1981). This situation, along with other related factors, has pointed to the need for improved understanding of the cognitive processes of a tactical commander in situation assessment and resource allocation prior to further decision aid development. Third, these models can be used to examine the external validity of the decision making research results gleaned in laboratory settings (Einhorn and Hogarth, 1981). That is, they can help answer questions such as: Do the judgmental biases and apparently irrational choice behaviors found in the laboratory hold in specific operational decision contexts? Fourth, the development and real-world application of cognitive models should help to identify new theoretical research issues for both mathematical and experimentally oriented cognitive psychologists.

This report describes the formulation and computer implementation of a cognitive model of an anti-submarine warfare commander's (ASWC's) tactical decision process. The model addresses the ASWC's aircraft mission assignment tactical decisions. On the basis of imperfect information, from geographically distributed sensors, on the positions of enemy submarines, the ASWC's task is to decide how best to allocate his aircraft to detect and to deter these enemy submarines.

1.1 RESEARCH METHODOLOGY

The ASWC tactical decision model is constructed using the SHOR paradigm (Wohl, 1981) of human decision making as a modeling framework. This framework describes the decision process as a cascading of four activities: (1) information processing, (2) hypothesis generation and evaluation, (3) option generation and evaluation, and (4) action execution (Wohl, 1981; Wohl et al., 1983)

The mathematical representations used to characterize the decision making activities are normative-descriptive (Rapoport, 1975). The normative-descriptive approach to human modeling was pioneered by Toda (1962) and Shuford (1964). The essence of this approach is the coupling of optimal models of procedural rationality (Simon, 1979) that prescribe how decisions should be made with constraints or limitations that are "psychologically interpretable and consistent with current psychological knowledge" (Rapoport, 1975, p. 355). According to Sheridan and Ferrell (1974, p. 321):

> As a rough approximation people do what they ought and hence descriptive theories or models have frequently been adaptations of normative ones, discrepancies between predicted and actual behavior usually being attributable to noise, misunderstanding, errors, and the like. The discrepancies matter to the systems designer since he generally tries to reduce them. Interested both in measuring and predicting performance and in assessing and improving performance quality, he must concern himself with both kinds of model (normative and descriptive)...

Normative-descriptive modeling can be construed as constrained optimization. And human decisions "may be interpreted as optimal under given perceptual, intellectual, and cognitive biases or limitations" (Rapoport, 1975, p.355). By varying the constraints, a normative-descriptive model can

reflect: (1) individual differences in decision making, and (2) the effects of decision-aiding technologies.

The anti-submarine warfare (ASW) simulation model is comprised of two components: a model of the ASW environment and an ASWC tactical decision model as shown in Fig. 1-1. The environmental model simulates the dynamics and operational characteristics of the ASW platforms, ASW sensors, and enemy submarines. It outputs the sensor data and the own-force platform states to the ASWC model. On the basis of the output from the environmental model, the ASWC tactical decision model makes the aircraft mission assignments. The ASWC model is built of two submodels: a model that represents the ASWC's hypothesis generation and evaluation procedure (situation assessor), and a model that represents the ASWC's option evaluation procedure (resource manager). The purpose of the situation assessor is to transform the imperfect contact data on multiple submarine targets from distributed sensors into coherent position and velocity estimates for the targets. Given these estimates and the own-force states, the resource manager makes the following aircraft allocation decisions: (1) which aircraft to send, (2) the aircraft's destination, and (3) what target localization maneuver the aircraft is to employ. These actions are then input to the environmental model as shown.

The normative models used to represent the ASWC's situation assessment and resource management activities are drawn from the broad disciplines of the detection and estimation theory (Van Trees, 1968) and the statistical decision theory (DeGroot, 1970), respectively. The descriptive models are drawn from the cognitive and behavioral sciences (Slovic et al., 1977; Einhorn and Hogarth, 1981). Descriptive concepts from the literature are transformed into functional mathematical representations that dovetail with the normative

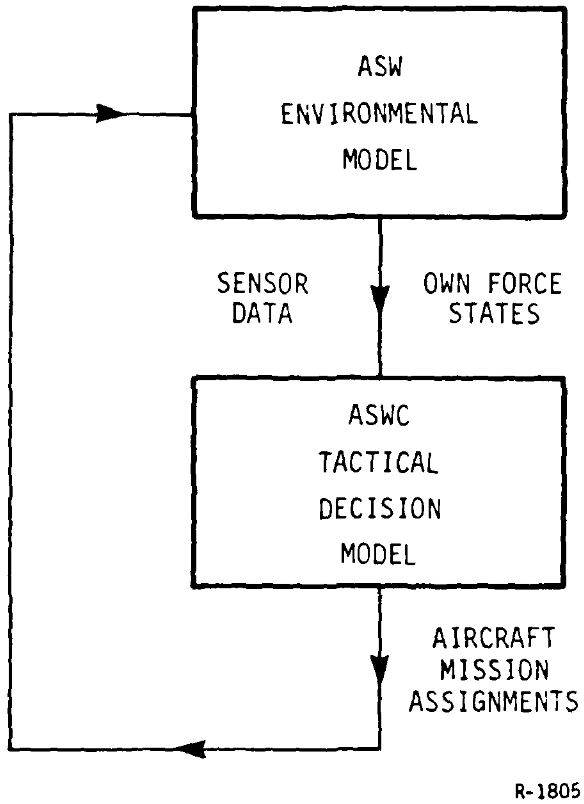


Figure 1-1. Diagram of the ASW Simulation Model

models of the ASWC's cognitive activities. In particular, the ASWC model encodes descriptive research findings concerning human information processing and choice making behavior under conditions of uncertainty and stress.

1.2 OUTLINE OF THE REPORT

The classified nature of the real-world domain of the model precludes completely accurate replication of the ASW environment and the ASWC's tactical decision process. The models developed herein are, thus, abstractions of reality. These abstractions, however, capture the essence of the ASW decision problem without compromising classified information.

The report is structured as follows. Section 2 provides a description of the factors that affect the ASWC's decision making. These factors include the acoustic environment, own-force asset capabilities, and the characteristics of the opposition. A description of the ASW-relevant cognitive psychological issues comprises Section 3. Section 4 describes the normative and descriptive mathematical representations of the ASWC's two primary cognitive activities: situation assessment and resource management. Section 5 describes the performance of the model in a hypothetical ASW scenario and presents model parameter sensitivity analyses. A summary of the report and recommendations for future research are offered in Section 6.

SECTION 2

ANTI-SUBMARINE WARFARE

The mission of anti-submarine warfare is to detect and to deter hostile submarines so as to ensure the safe and timely transit of own-force platforms. The mission is comprised of three activities. First, the hostile submarine's presence must be discovered and confirmed (detection and prosecution). Second, the submarine's location must be determined (localization). Finally, the hostile submarine must be destroyed (attack). In this report, only the first two activities are addressed.

Successful execution of ASW operations (detection, prosecution, localization) depends on four factors. They are:

1. The ambient acoustic and meteorologic conditions.
2. Own-force asset capabilities.
3. The nature and tactics of the opposition.
4. The strategic and tactical acumen of the ASW commander and his staff.

When at sea, the first three factors are the ASWC's states of nature. Keen understanding of the principles of the propagation of sound through the water and the effects of the meteorologic conditions thereon is requisite since underwater sound (sonar) is virtually the only means of detecting submerged submarines. This expertise must then be coupled with a firm grasp of own-sensor accuracies and reliabilities to effectively process and integrate incoming sonar data. The sonar data and prior knowledge concerning the

opposition's tactics and procedures are the sufficient inputs for ASW tactical decision making. The aggregation of this knowledge is the commander's mental model of ASW.

The purpose of this section is to provide elementary descriptions of the principles of the underwater acoustic environment, the ASW assets and sensors, and the nature of the ASW threat. The final subsection describes how this information bears upon the ASWC's decision process.

2.1 ASW ACOUSTIC ENVIRONMENT

Sound is the only form of radiation that is not rapidly attenuated in water. As a sound wave propagates through water, its velocity and, thus, direction are affected by the temperature, pressure, and salinity of the water. The energy of the sound wave is diminished because of wave divergence, desorption, scattering, reflection, and refraction that occur as a result of the state of the water and the prevailing boundary conditions. These phenomena and the presence of ambient background noise render the analysis of underwater sound complex.

2.1.1 Underwater Sound Propagation Paths

The velocity profile, i.e., the graph of velocity of sound in water with depth, is directly related to the temperature, pressure, and salinity of the water. The velocity of sound increases with temperature, pressure, and salinity.

The temperature of the water changes with depth. When the water has a negative thermal gradient (temperature decreases with depth), the sound energy is refracted away from the surface. The converse is true when a positive thermal gradient exists. The pressure in the water increases uniformly with

depth. Thus, as the sound wave travels deeper its velocity increases. Similarly, sound travels faster with increasing salinity.

In the ocean, the pressure and salinity variations with depth are predictable. It is the thermal gradient that dictates the propagation characteristics. The thermal gradient is stratified into three layers: (1) surface layer, (2) thermocline layer, and (3) deep layer. A fairly isothermal gradient exists in the surface layer because of surface mixing. The thermocline layer has a distinct negative thermal gradient. A shallower negative thermal gradient comprises the deep layer.

In deep water there are three principle propagation paths. They are the direct path, the convergence zone paths, and the bottom-bounce paths. The presence of these paths depends on the thermal gradient, the depth of water, and the geologic conditions of the sea bottom.

When the sound source is located in the surface layer and there is a positive velocity gradient in the layer, then direct path acoustic propagation occurs. The sound waves are refracted upwards because of the velocity gradient and are reflected downward by the surface as shown in Fig. 2-1.

Convergence zone propagation paths occur when sound waves generated in the surface layer penetrate the layer, travel downwards, and are then refracted upwards because of pressure effects. The depth of the water must usually be greater than one mile to encounter convergence zone conditions. The convergence zone propagation phenomenon is diagrammed in Fig. 2-2. The convergence zone range and width are determined by the depth and velocity excesses. The depth excess is the difference between the depth of the bottom grazing ray and the deep layer depth at which the velocity of the sound wave is equal to the velocity at the surface layer depth. The velocity excess is

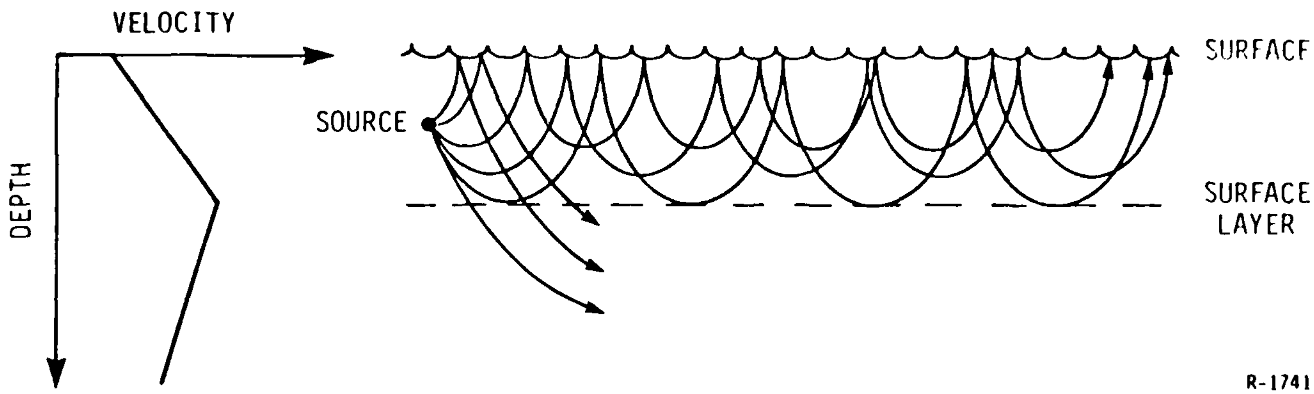


Figure 2-1. Direct Path Propagation (Hurley, 1980)

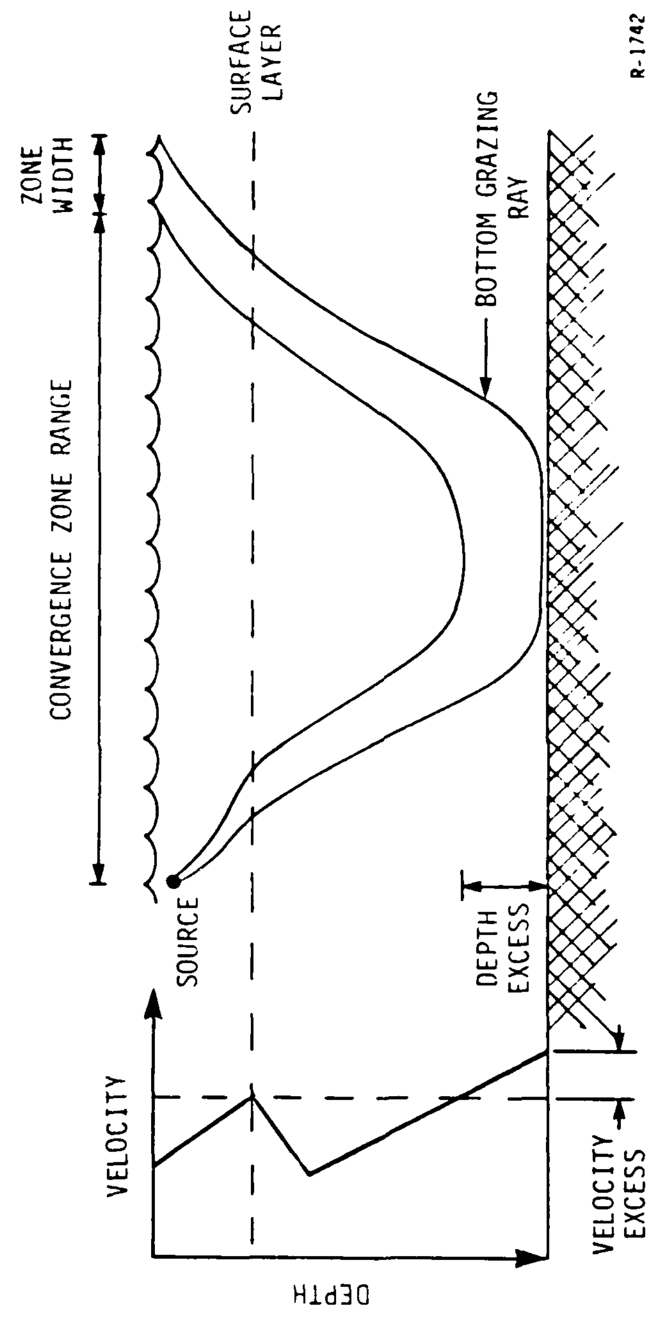


Figure 2-2. Convergence Zone Propagation (Hurley, 1980)

defined as the difference between the velocities at the depths used in the depth excess calculation. Multiple convergence zones are present when the sound waves reaching the surface in the zone are again reflected. These conditions prevail when the velocity and depth excesses are great. Convergence zone ranges can typically vary between five and forty-five miles in the ocean. Convergence zone widths range between five and ten percent of the range (Urich, 1975).

Bottom-bounce propagation paths, shown in Fig. 2-3, occur when (1) the shallow depth of the ocean precludes the sound wave from obtaining a depth sufficient for convergence zone propagation, or (2) the depression angle of the sound wave is greater than 15°. The incidence angle of the sound wave is dependent on the reflectivity of the ocean bottom. The bottom-bounce phenomenon is independent of the temperature profile since the depression angles are substantial.

2.1.2 Underwater Sound Propagation Loss

The energy of a sound wave is diminished as it propagates through any medium. The sound wave propagation loss is defined as the difference in the magnitude of the intensity level (decibels, dB) of the acoustic signal at the source and at the receiver. Three phenomena contribute to the loss of signal intensity: (1) spreading loss, (2) absorption loss, (3) and reflection loss.

A sound pulse emitted through an ideal medium (frictionless, homogeneous, and unbounded) radiates spherically. Since the medium is ideal, the power (the product of the area of the sphere and the intensity of the signal) on any size sphere must be the same. Therefore, the intensity of the signal is inversely proportional to the square of the radius of the sphere. The spreading

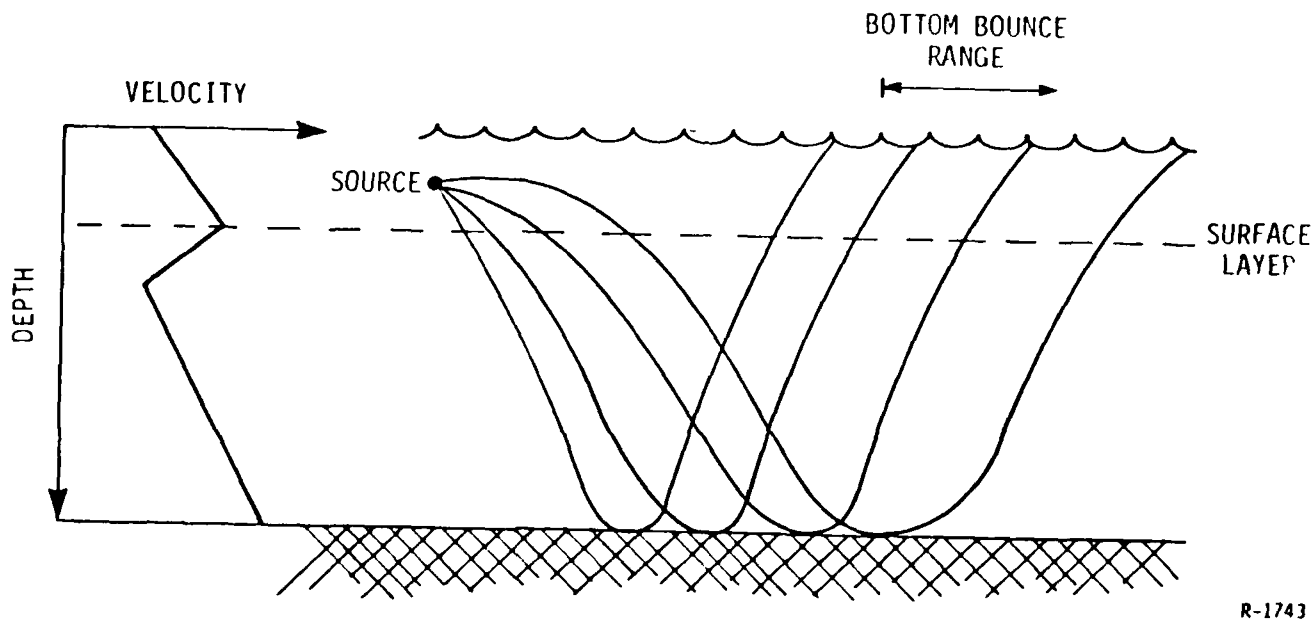


Figure 2-3. Bottom-Bounce Propagation (Hurley, 1980)

in the ocean however, is roughly cylindrical because of the surface and bottom boundaries. The spreading loss in a cylinder is inversely proportional to the radius of the cylinder.

As a sound wave propagates through the water, energy is lost in the form of heat. The heat is generated by intermolecular friction. This acoustic energy loss is the absorption loss.

Underwater acoustic waves reflected at the ocean surface and bottom are subject to energy loss because the boundaries are not perfect reflectors. Acoustic energy is absorbed because the boundaries are not impenetrable and because they are often ill-shaped, thus scattering some of the energy. Other sources of reflection loss are marine life and air bubbles caused by rough seas.

2.1.3 Sonar Principles

There are two types of sonar systems: active and passive sonars. Active sonars emit acoustic energy and listen for its reflection, or echoes, to detect targets. This echo-ranging supplies reliable information concerning the range to the target and bearing of the target. Passive sonars merely listen for the acoustic energy produced by the target. They provide precise bearing, reliable classification (identification), and poor range information about the target.

Active sonars produce many false alarms. These erroneous detections can be attributed to the reflection of the sound pulse by whales, schools of fish, and shoals. Passive sonars produce fewer false alarms. The noise generated by the submarine is described by the amount of power radiated at different frequencies as shown in Fig. 2-4. These tones are generated by rotating

machinery. It is the pattern of these tones that identify the sound source and enable the sonar operator to determine a submarine's class.

The detection range of a sonar, either active or passive, is predicted using the sonar equations (Urich, 1975). The equations combine information about the source of the acoustic energy, the state of the medium, and characteristics of the receiver. For an active sonar, the intensity of the acoustic echo at the sound source and receiver DT is given by

$$DT = SL-2TL+TS-(NL-DI),$$

where

SL = intensity of the sound radiated at the active sonar [dB],

TL = transmission loss in the medium [dB],

TS = reflected intensity of the incident acoustic pulse by the the target [dB],

NL = ambient background noise in the medium [dB],

DI = directivity index [dB].

SL and DI, the capability of the receiver to discriminate against noise on all bearings save the bearing of incident acoustic energy, are parameters of the active sonar. TL and NL, the noise of the ocean and man-made noise, are parameters of the medium. TS is a parameter of the target. The detection threshold DT is the signal-to-noise ratio. When DT is large (probability of detection approaches one), the false alarm probability approaches zero.

The detection range of the sonar is determined as follows. Parameters SL, TS, NL, and DI of the active sonar equation are considered known and fixed. The detection threshold is specified to ensure a minimum acceptable probability of detection. Hence, the transmission loss TL, which is range dependent, is determined. Thus, the range at which detection is possible with

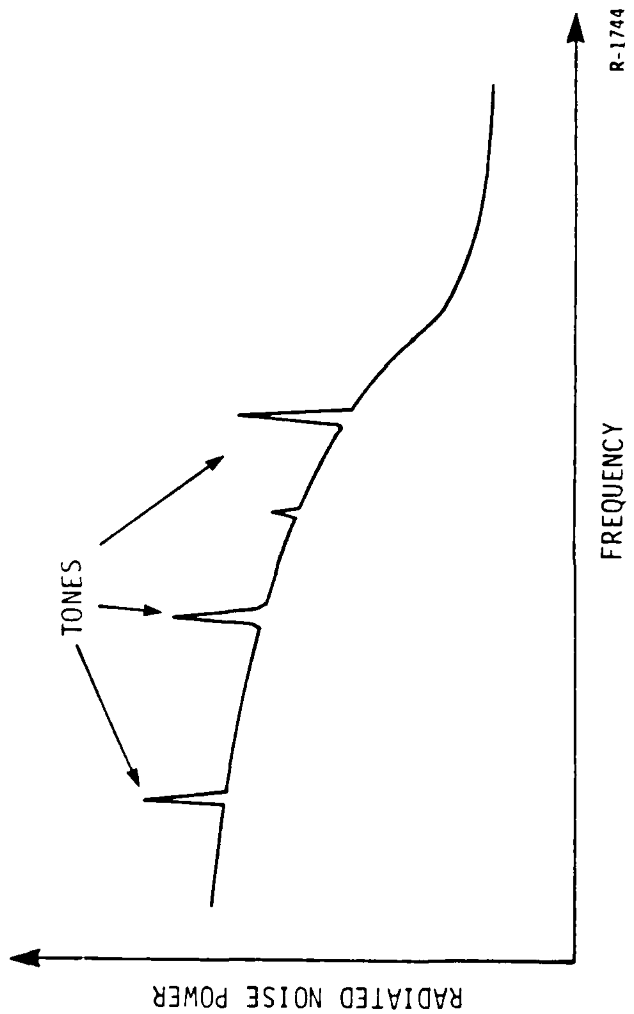


Figure 2-4. Radiated Noise of a Submarine

a given probability is computed. Note that in the presence of convergence zones, TL is not a monotonically increasing function with range.

The passive sonar equation is simply defined as

$$DT = TS-TL-(NL-DI),$$

where TS is the acoustic intensity radiated by the target [dB]. The procedure for determining the passive sonar detection range is analogous to the active sonar procedure.

The detection range calculation is, however, imperfect. The estimates of the states of ocean (its temperature, salinity, and depth profiles), or TL and NL, are fraught with uncertainty because: (1) the measuring devices are not error free, and (2) the ocean is nonhomogeneous. The acoustic intensity of the target, TS in the passive case, changes with the speed, depth, and type of the target. Moreover, the relationship between DT and the probability of detection is empirical. It depends on the characteristics of the signal processing hardware and the sonar technician.

2.2 ASW ASSETS AND SENSORS

The battle group is the basic unit of the Navy. A battle group consists of an aircraft carrier (CV), six to ten surface escorts--primarily frigates (FF), destroyers (DD), and cruisers (CG)--and one or two direct support attack submarines (SSN/DS).

2.2.1 ASW Assets

The aircraft carrier usually embarks one squadron of anti-submarine fixed-wing aircraft (S-3A) and one squadron of anti-submarine helicopters (SH-3H). Surface ships specialized for anti-submarine defense (frigates,

Spruance-class destroyers, etc.) are equipped with a single anti-submarine helicopter (SH-2F or LAMPS II). These aircraft, helicopters, and the ASW-capable ships constitute the ASWC's assets.

All surface and subsurface escorts have both a passive and active sonar capability. The aircraft have passive and active sonobuoys and a Magnetic Anomaly Detector (MAD) that senses the distortions in the earth's magnetic field caused by a submarine's presence. The SH-3H helicopters have dipping sonars.

Surface and subsurface assets have specific ASW roles. These roles are dictated by the platforms' operational characteristics. Operating speeds are rarely in excess of 30 knots (Dunnigan, 1982) and optimum sonar speeds are between 15 and 20 knots. This limitation severely constrains the platforms' abilities to search for targets, though they do have virtually unlimited endurance. Furthermore, they are detectable and are vulnerable to attack by subsurface targets. Thus, the most useful way to employ these assets is in defense of the aircraft carrier. This function is termed screening. The platforms are disposed about the carrier so as to minimize the probability of the enemy submarine approaching the carrier undetected. The sonar screen created by the formation serves as the source of most of the initial detections of enemy submarines. The screen effectiveness is extended by the presence of the ASW ships that can dispatch their LAMPS II helicopters quickly to prosecute detections without disrupting the sonar screen.

The ASW fixed-wing aircraft counterbalance some of the surface escorts' tactical limitations. They can transit at speeds greater than 400 knots (Dunnigan, 1982). Thus, their reaction time is fast, and their ability to search large areas great. They are invulnerable to attack from submerged

submarines. Their endurance is from six to eight hours. These attributes make the S-3A an ideal platform to: (1) monitor sonobuoy barriers outside the battle group formation, thus extending the force's detection range, and (2) pursue, track, and localize long-range detections.

The ASW helicopters represent an operational compromise between the S-3As and the surface escorts. They transit at speeds greater than 100 knots and have an endurance of roughly four hours. They, too, are invulnerable to attack from a submerged submarine. When deploying sonobuoys, the helicopter must be within radio range of a surface platform as it has no signal processing capability of its own. These helicopters enable individual ASW platform commanders to respond immediately to detections from short-range sonars. They are also used in coordination with the ASW fixed-wing aircraft. The coordinated action is effective because the helicopter is a more capable platform for localization and attack.

2.2.2 ASW Sensors

There are four sources of an initial detection of an enemy submarine. They are: (1) strategic intelligence, (2) visual sightings, (3) radar detection, and (4) sonar detection. These sources convey information, of varying accuracy, concerning the location and type of the enemy submarine.

Strategic intelligence data are generated by the Sound Surveillance System (SOSUS) network and the Surveillance Towed Array System (SURTASS). SOSUS is a network of passive hydrophones that reside on the edge of the continental shelves of the North Atlantic and Pacific oceans (Dunnigan, 1982). SURTASS is a long array of passive hydrophones that is slowly dragged by a surface platform in the open ocean. These strategic data are relayed to land

stations, via cable or satellite, where they are processed and disseminated. As with all passive sensors, the bearing and classification information about the submarine obtained are reasonably accurate. The range, however, is unpredictable. Thus, only when the data processing and dissemination times are minimized can these data be tactically useful.

Visual sightings of hostile submarines are often obtained by aircraft on the way to and from missions not related to ASW search. The sightings generally occur outside the range of the battle group's radars and sonars. These detections provide the commander with accurate information concerning the location of the submarine and frequently the type of submarine. Reporting delays and the delays imposed by the flight time of an ASW aircraft to datum, however, make even these targets difficult to redetect and localize.

Surfaced submarines--or those with their periscopes, snorkels, or antennae above the surface--can also be detected by radar. Radar detections provide only accurate position information. The redetection and localization opportunities are situation-dependent.

The final sources of an initial detection are the active and passive sonars indigenous to the battle group. Surface and subsurface escorts are equipped with any or all of the following generic sonar devices: hull-mounted sonar, independent variable-depth sonar (IVDS), and tactical towed array sonar (TACTAS). ASW aircraft (rotary-wing and fixed-wing) employ dipping sonar, sonobuoys, and MAD.

Hull-mounted sonar. This sonar has an active and passive capability. Because of own-ship noise, this sonar can not detect targets in the stern sector. The existing sound propagation paths, the states of the ocean, the speed of the platform, and the depth of the target largely determine the detection

range of the sonar and its expected bearing error. The hull-mounted sonar data are subject to great uncertainty when the target is operating below the surface layer depth.

Independent variable-depth sonar. The IVDS is an active sonar that is lowered beneath the surface layer depth and towed behind the platform. As such it does not suffer the operational deficiencies of the hull-mounted sonar. Sonar coverage is a full 360 degrees, and it can detect targets operating below the surface layer. The only deficiency is its active-only capability. Its performance depends on the same parameters as the hull-mounted sonar.

Tactical towed-array sonar. TACTAS is an array of passive hydrophones towed at below-layer depths behind a surface or subsurface escort. Sonar coverage in the bow sector is restricted because of own-ship noise. Under ideal conditions, TACTAS can detect targets in the third convergence zone. The TACTAS bearing error is not only a function of the environmental parameters and own-ship speed, but also the actual bearing to the target. Obtuse bearings, i.e., for targets far to the stern of the array, are subject to greater error than are acute bearings. These arrays also provide excellent classification information on the target if the contact can be maintained. Range to the target can sometimes be inferred from the bearing rate of the target.

Dipping sonar. This is an active sonar used by helicopters. The sonar device is lowered by cable, to a depth of up to 500 feet, to search one bearing at a time for the target. Once the sonar is trained on the correct bearing, localization ensues because the sonar can be readily moved closer to the target. These sonars are capable of detections only in the direct path range.

Sonobuoys. These small passive listening devices are dropped into the ocean in the vicinity of submarines by aircraft. Their outputs are radio-transmitted to the aircraft. These signals are processed either on-board the aircraft or the aircraft provides a link to a nearby surface platform. Omni-directional, or LOFAR, sonobuoys transmit only the raw acoustic signal. DIFAR sonobuoys provide information on the bearing to the target. Detections beyond the direct path range occur only under ideal environmental conditions.

Magnetic anomaly detector. MAD is infrequently used as an initial detector because its effective range is less than a kilometer (U.S. Naval Academy, 1977; Dunnigan, 1982). After localizing the submarine with sonobuoys to a small area, MAD is employed to localize further the submarine to attack criteria.

2.3 ASW THREAT

The type of submarine, or submarines, attacking an aircraft carrier battle group determines the nature of the ambush. Attack submarines are either diesel-electric powered (SS) or nuclear powered (SSN). Some submarines employ anti-ship cruise missiles (ASCMs) and some employ torpedoes as their principal weapons.

Diesel-electric submarines are ideal for patrol and reconnaissance as they radiate little acoustic energy when operating on battery power. In fact, they are virtually impossible to detect passively. They must, however, subject themselves to detection every few hours while running on diesel to replenish the battery power by surfacing or snorkeling. Furthermore, the diesel engines are noisy. These submarines operate at ten to fifteen knots when submerged. They are capable of speeds up to twenty knots when at the surface.

Nuclear powered submarines, on the other hand, have unlimited endurance and are capable of submerged operating speeds in excess of 25 knots (Miller, 1982). These operational improvements are offset by the fact that these submarines are detectable by passive sonars.

ASCMs can be launched at targets from 30 to 300 nautical miles [nm] (Dunnigan, 1982; Miller, 1982). The long-range cruise missiles generally must be fired from the surface and require midcourse guidance from another ship, submarine, or aircraft. The short-range cruise missiles (< 100 nm) are fired while the submarine is submerged. These missiles require no external guidance; the targets are located by the submarine's own sonar.

Torpedoes have a range of up to 30 nm. There are two types of torpedoes: wire-guided torpedoes and acoustic sensing torpedoes. Wire-guided torpedoes feed back acoustic information to the fire control operator for more precise mid-course targeting. Acoustic sensing torpedoes are dispatched along the bearing determined by the submarine's sonar, and use their own acoustic sensors to accurately seek the target.

Some broad conclusions concerning an anti-carrier ambush are evident. First, torpedo-armed submarines can be used to fire a torpedo at the carrier or to provide targeting information for a submarine armed with cruise missiles. Second, in either capacity diesel-electric submarines must have accurate prior knowledge of the battle group's trajectory and speed of advance. This knowledge is requisite since battle groups often transit at speeds in excess of the maximum operating speeds of the diesel-electric submarines. The threat sector posed by diesel-electric submarines is therefore restricted to the carrier's heading ± 90 degrees. Third, the submerged operating speeds of nuclear submarines enable them to stalk and hunt down carriers. Thus, they

pose a 360-degrees threat to the carrier. Fourth, short-range cruise missile nuclear submarines are wont to act independently because they can: (1) do their own targeting and (2) stalk the battle group waiting for an appropriate opportunity.

The determination of the class (type) of any submarine in the presence of the battle group is the key to assessing the ASW threat. In all but a few cases, perfect knowledge of the submarine class implies perfect knowledge of the type and maximum range of the submarine's weapon. Without this information, the ASW commander can form no reliable hypotheses about the intent or tactics of the submarine.

2.4 ASW DECISION PROCESS

In this report, the ASWC's decisions are divided into two categories: strategic and tactical. Strategic decisions are defined to be those made before a hostile submarine is detected by the battle group's own sensors. The decisions made subsequent to the initial detection are deemed tactical.

2.4.1 Strategic Decisions

Among the most important ASW-relevant strategic decisions are the battle group's: (1) composition, (2) disposition (screen), (3) trajectory and speed of advance, and (4) electromagnetic and acoustic emission control (EMCON) policy. These decisions are all coupled, i.e., one decision can not be made independently of the others.

Prior to sailing, the Officer in Tactical Command (OTC) of the battle group thrashes out these decisions with his warfare area commanders. When at sea, all decisions, save the force's composition, can be adapted in response to real-time tactical information.

The factors that affect these decisions are the battle group's mission, the expected capabilities of the opposition to be encountered en route, the expected acoustic and meteorologic conditions, and own-force capabilities.

Force composition. The composition of the carrier escort force depends principally on the nature of the threat and the acoustic conditions. For example, if the cruise missiles launched from enemy planes and surface ships constitute the perceived major threat to the carrier, the force will emphasize surface assets that are specialized for anti-air warfare (AAW). Analogously, if torpedoes fired from submarines constitute the perceived major threat, the force will emphasize surface assets that are specialized for ASW. When cruise missiles launched from submarines are of concern, both AAW and ASW-specialized ships will comprise the force, since launched cruise missiles are air threats.

Force disposition. The purpose of the screen of surface and subsurface escorts arranged about the carrier is to provide the maximum protection against any air, surface, or subsurface threats. The composite nature of the threat dictates that any solution will be a compromise. The best strategy against a cruise missile attack on the carrier is to position all escorts with AAW capability (note that ships specialized for one warfare area have capabilities in the other areas) close to the carrier and in the air-threat sector. Conversely, an anti-submarine screen has its surface escorts dispersed and distant from the carrier. This formation provides maximum sonar coverage and degrades enemy submarine counterdetection opportunities. The precise arrangement depends on the priorities assigned to each threat, the acoustic conditions, and the speed of advance.

Battle group trajectory and speed of advance. The urgency of the mission, the oceanographic and acoustic conditions, own-force capabilities, and

the nature of the threat affect these decisions. Often two defensive postures exist. First, the battle group can transit a route where good acoustic conditions prevail. In this situation, the OTC is gambling that his own sensors will detect any enemy submarine. In this case the speed of advance is usually chosen near the optimum sonar speed of his longest-range-sonar platform. Second, the battle group can transit a route where poor acoustic conditions prevail. The OTC is gambling that the environmental conditions will preclude counterdetection by the enemy submarines. The more unfavorable the acoustic conditions, the higher the speed of advance will be.

EMCON. Herein, only the acoustic emission control (ACCON) policy is addressed. The battle group's ACCON is designed to minimize the counterdetection capability of adversary submarines and to maximize the range and reliability of own-force detections.

Counterdetection opportunities arise from noise radiated by own force platforms and the use of active sonars in the battle group. Thus, counterdetection is minimized by operating at slow speeds, using only passive sonars.

Passive operation is also desirable when convergence zone or bottom-bounce propagation paths exist, as these conditions can not effectively be exploited by active sonars. However, passive systems are subject to mutual interference with other platforms and can not detect diesel-electric submarines.

The degree of active or passive acoustics the battle group should rely on is tied intimately to the expected threat, the acoustic conditions, and own-force platform active and passive sonar suites.

2.4.2 Tactical Decisions

The key ASW tactical decision makers are the ASWC and his staff, the surface platform commanding officers and their ASW coordinators, and the captains of the direct support attack submarines. The principal duties of the ship commanding officers and submarine captains relative to ASW are: (1) to implement the ACCON policy and (2) to apprise the ASWC of any significant ASW information or events.

Subsequent to the initial detection of a hostile submarine, any of the following tactical decisions can be made. They are:

1. To recommend or request that the OTC alter the battle group's ACCON policy to degrade counterdetection or improve own-force detection opportunities.

2. To recommend or request that the OTC modify the battle group's trajectory and/or speed of advance to deny the opposition targeting information (evasive steering).

3. To redesign the sonar screen by repositioning platforms.

4. To deploy a surface platform or aircraft to prosecute a contact or localize a target.

The ASWC and his immediate staff have the authority to make any of the above decisions. However, the repositioning of ships specialized for air or surface warfare must be coordinated with their respective warfare area commanders. The commanders of ASW-capable ships are accorded the responsibility of independently directing their own ships and own-ship ASW helicopters for contact prosecution and target localization.

ACCON policy. The most serious real-time ACCON policy modification is the decision to use active sonar on a submarine that was initially detected using passive-only sensors. This action is recommended when the submarine is applying evasive maneuvers or when the threat posed by the submarine outweighs the benefit of being covert.

Evasive steering. Unscheduled modification of the battle group's trajectory and/or speed of advance is difficult to coordinate and results in transit time delays. Thus, this action is reserved for situations in which the threat is imminent.

Screen reorientation. Surface ships are often repositioned to cover gaps left in the sonar screen by platforms on search maneuvers and to cross-fix a sonar contact with another platform already holding contact. When the repositioning of a surface platform is infeasible, dipping-sonar helicopters or sonobuoy barriers monitored by helicopters are used to maintain the integrity of the sonar screen.

Platform assignment. The decision to send a platform (surface, subsurface, or aircraft) to prosecute a contact or to localize a target entails many subdecisions. They are to decide: (1) which platform to send, (2) the destination of the platform, and (3) the search or localization maneuvers employed by the platform. The objective is to deploy the asset that maximizes the probability of redetecting the submarine and minimizes the opportunity cost should this action be unsuccessful. Colloquially: Send the least capable asset that can get the job done.

The platform's time-late-to-datum (transit time), the amount of time it can search or patrol an area (time-on-station), the effectiveness of its ASW sensors in the ambient acoustic environment, and the uncertainty concerning the hostile submarine's actual location are the fundamental characteristics that determine the probability of redetection. For example, it is infeasible to use a surface platform to prosecute convergence zone contacts because its time-late is too great. Equivalently, aircraft with limited fuel and few sonobuoys are not admissible alternatives.

An opportunity cost is incurred by the battle group when a surface platform is detached from the screen to prosecute a contact or to localize a target. This cost represents the degradation in the ASW and AAW screens because of the platform's absence. Ultimately, there is no tangible penalty, or cost, unless the battle group suffers a cruise missile or torpedo hit while the platform is out of position.

There is a tangible opportunity cost every time an aircraft is sent on an ASW mission. After a fixed amount of flight time, all aircraft (rotary- and fixed-wing) must undergo a comprehensive servicing. Thus, extensive use of an aircraft over a short period of time ensures its unavailability thereafter. The other component of opportunity cost is the effect of crew fatigue. Fatigue results from flying many missions or being in a high-readiness condition (on the deck, sitting in the aircraft) over a long period of time. Fatigued crews perform poorly and will be unavailable for action following a period of hectic activity.

SECTION 3

ASW-RELEVANT COGNITIVE ISSUES

This section identifies the cognitive and behavioral factors that are relevant to the modeling of ASWC decision performance.

Literature of behavioral decision theory and other relevant cognitive theories identifies heuristics, cognitive biases, and other cognitive limitations exhibited by humans in deliberative activities. However, much of the cognitive and behavioral research was performed in university laboratories, and most studies tend to be context-free. Thus, a rational coupling of cognitive theory and research results to the ASW tactical decision making environment is a primary objective of this effort.

To provide this rationale and to identify the cognitive and behavioral issues germane to the ASW decision context, interviews with ASW personnel, site visits to ASW training facilities, and an extensive literature review were performed. The information thus obtained was then subjected to a cognitive task analysis.

Our analysis of the ASW environment and the cognitive demands placed on ASWCs indicates that the applicable behavioral decision theory and cognitive literature can be grouped into three categories: 1) information processing, 2) choice making, and 3) a "catch all" class of other cognitive issues (e.g., short-term memory and stress).

Information processing includes both hypothesis generation and evaluation (i.e., situation assessment) and the ways in which decision makers process and integrate information for that purpose. Numerous contemporary studies in cognitive psychology (see for example Slovic et al. (1977) or Einhorn and Hogarth (1981) for comprehensive reviews) have uncovered various heuristics and biases that decision makers apply in interpreting and aggregating probabilistic information. Choice making is concerned with the procedures that decision makers employ to identify and choose among alternative courses of action. The cognitive effects associated with short-term memory (STM) capacity and long-term memory (LTM) accessibility and those related to stress affect both the decision maker's estimates of the states of nature (information processing) and the perceived options open to him (choice making). An additional cognitive factor that appears relevant to ASWC decision making, the threshold for action, is identified. It describes the minimum situational change needed to trigger an action.

3.1 INFORMATION PROCESSING CHARACTERISTICS

The cognitive task analysis shows the tempo of ASW to be slow and deliberate. In general, ASWCs are afforded sufficient time to contemplate available information and select courses of action. However, they must deal routinely with uncertain and probabilistic information, something the behavioral decision literature has shown to be quite difficult for most individuals (Phillips et al., 1966; Sage, 1981). In the words of Slovic. (1982, p.159), "...people systematically violate the principles of rational decision making when judging probabilities, making predictions, or otherwise attempting to cope with probabilistic tasks." As Hammond (1974, p.4) puts it, the reason may be that "... man's cognitive capacities are not adequate for the tasks which

confront him;" or as more bluntly stated by Slovic (1982, p.158), "...work has led to the sobering conclusion that, in the face of uncertainty people's intuitive judgments and decisions violate many of the fundamental principles of optimal behavior." The fact is that humans are far from perfect when forced to account for uncertainty or to process probabilistic information.

There is no reason to believe that ASWCs will fare much better than the individuals addressed in the research. Like most people, they will attempt to adopt strategies to cope with their own inherent cognitive limitations and to simplify the situation by applying strategies or heuristics. These learned techniques serve to reduce mental workload so that judgments can be made; however, they also lead to serious, persistent biases in the decision making process (Slovic et al., 1977).

The literature of behavioral decision theory and cognitive psychology is replete with descriptions of various intuitive strategies and cognitive biases exhibited by people, including experts, in interpreting and aggregating probabilistic information, e.g., Slovic et al. (1977); Einhorn and Hogarth (1981); Sage and White (1980); and Sage (1981). From these cognitive characteristics we select the following subset for discussion because (1) they appear relevant to critical ASWC functions or (2) they have been shown to be particularly important in the behavorial literature: adjustment and anchoring, availability, conservatism, hindsight, law of small numbers, misperception, overconfidence, and representativeness.

Adjustment and anchoring. This heuristic is often invoked when there appears to be a glut of information. To deal with this a person first selects some initial value or "anchor" (such as the mean or an extremum) to be used as the first approximation to the judgment. To accommodate the implications

of additional information, adjustments are then made to the anchor. Unfortunately, such adjustments are imperfect and insufficient (i.e., non-Bayesian, tending toward some sort of averaging effect), thus leading to flawed judgments (Tversky and Kahneman, 1974). Slovic (1982) further points out that people believe that they have a much better picture of the truth than they really do, that their confidence intervals are overly narrow, and that they tend to overestimate the probabilty of conjunctive events while underestimating the probability of disjunctive events. Anchoring and adjustment in a sequential task is termed primacy/recency (Lopes, 1981; Lopes, 1982).

Availability. Another judgmental bias discussed by Tversky and Kahneman (1973) notes that if an event is easy to recall or imagine, then it is also judged to be more likely or more frequently occurring. The rationale given is that instances of frequently-occurring events are typically easier to recall than instances of less frequently-occurring events. Similarly, probable occurrences are usually easier to imagine than improbable occurrences. Thus, availability appears to be a valid indication of an event's probability. Availability, however, is prone to the effects of a number of factors unrelated to true event likelihood. If availability is used, systematic overestimates of the likelihood for recent, familiar, or otherwise salient events will occur.

Conservatism. This refers to the failure to give new information as much weight or credibility as Bayesian decision theory would predict. Hence, prior estimates are not revised as much as they should be given new significant information (Phillips et al., 1966; Slovic and Lichtenstein, 1971; Sage, 1981). It is directly related to the primacy effect in anchoring and adjustment.

Hindsight. This is a bias dealing with the fact that individuals told that some event has occurred increase their belief that it was inevitable, and

as such was apparent in foresight, prior to the event. In other words, retrospectively individuals feel that they had a much better idea of what was about to transpire than they actually did have. Fischhoff (1975) has communicated that the hindsight bias poses a serious threat to correct evaluation of decisions made in the past and limits our ability to learn by experience.

Law of small numbers. This bias demonstrates people's insensitivity to sampling theory, whereby they underestimate the error and unreliability in small samples of data. Thus, individuals view a small sample as if it were a large sample and then consider it as highly representative of the population from which the sample was drawn (Tversky and Kahneman, 1971).

Misperception. This is a heuristic dealing with the misrepresentation of base-rate, mismatch between subjective and actual probability distributions, and the tendency to place greater belief in values closer to the mean--thus discounting the importance of rare events when they occur (Sage and White, 1980).

Overconfidence. People, in general, tend to ascribe higher probabilities to the occurrence of an event or their success than are warranted. This overconfidence can be seen in individuals': (1) estimates of their own abilities to perform a skill task (Howell, 1972), (2) miscalibrations of their probabilities for discrete and continuous propositions (Lichtenstein et al., 1982), (3) nonregressive predictions (Kahneman and Tversky, 1973), and (4) disregard for the extent of the data base upon which their judgments are based (Kahneman and Tversky, 1973).

Representativeness. Work by Tversky and Kahneman (1972) shows that when people are attempting to answer the question "does one object belong to a particular class of objects" or "what is the likelihood that a particular process

will generate an event", they examine the similarity between the classes. If after examining the essential features of the two entities (i.e., is one entity representative of the other) the entities are judged very similar, then the probability that an object belongs to a particular class or the probability that a particular process generates a particular event is considered to be high. Moreover, it has also been shown that this representativeness bias causes prior probabilities to be overlooked, predictions not to be properly regressed, and an insensitivity in considering data reliability (Kahneman and Tversky, 1973).

Several issues appear to be implied by these information processing characteristics. As with all people, we expect the ASWCs to exhibit some degree of cognitive bias and heuristic judgment. Furthermore, these biases can profoundly influence the information processing components of the ASWC's judgment and decision making activities. Lastly, it is unclear if people are consciously aware that they employ such heuristics (Payne et al., 1974), making behavioral change difficult.

3.2 CHOICE-MAKING CHARACTERISTICS

The primary cognitive characteristics that constrain the choice behavior of ASWCs as well as other decision makers are their limited combinatorial capabilities (directly ascribable to memory limitations) and the inherent randomness or subjectivity in their interpretation of value and/or success probabilities. The limitations that appear to be germane to the ASWC's option identification and selection are myopia, bounded rationality (satisficing), and bias in success probability.

Myopia. This involves the inability of the decision maker to project the effects of a potential decision far into the future. Thus, options are

evaluated using only a short time horizon that generally does not go beyond the next expected event. To a large extent, this may be the way that humans deal with (or avoid) consequence-of-action uncertainty, i.e., by keeping their real-time planning horizon short and relying on continual feedback from the environment. Discussions with ASW-trained personnel indicate that the ASWC tends to respond to all contacts by launching or redirecting an aircraft, even if it performs a maneuver that involves a very low probability of detection. However, by doing so the ASWC has put an aircraft in the air to respond to new data if and when it is received, thus simplifying future decisions and shortening the planning horizon.

Bounded rationality. Work reported by Simon (1957) shows that people act rationally with respect to their own simplified models but that such behavior does not even approximate optimality with respect to the real world. Decision makers often do not appear able, due to their inherent processing limitations, to evaluate all of the alternatives, and therefore they select the first alternative that will satisfy some minimal acceptance threshold. The observed result is referred to by Simon as satisficing behavior. The complexity of the asset selection problem, alluded to in earlier discussions, makes this characteristic particularly important to consider for the ASWC modeling task.

Bias in success probability. Decision makers tend to bias their estimated chance of success or failure. The factors that contribute to this are much the same as those discussed under information processing, and deal with strategies people use when having to assign probabilities to uncertain outcomes. In general, there is a tendency to allow for regressive effects (the gambler's fallacy). The probabilistic nature of ASW information leads to the inclusion of this characteristic.

3.3 OTHER FACTORS AFFECTING INFORMATION PROCESSING AND OPTION SELECTION

As stated by Rapoport (1975), it is the human's cognitive limitations and deficiencies, rather than his percetual or motor response limitations, that are the main limitations to consider when modeling human decision making. These limitations primarily involve the interaction between central processing functions and knowledge base. Thus, they may affect data aggregation, information processing, hypothesis and option generation and evaluation, and rank-ordering activities. Cognitive limitations and deficiencies are taken in this discussion to include short-term and long-term memory organization, interference effects, human biases, and heuristics. Generally, these types of limitations do not surface in manual control or in skill-based tasks where the link between sensory inputs and response/control is more direct and time-critical. They become particularly crucial, however, when dealing with judgment, decision making, and problem solving activities.

3.3.1 Short-Term Memory

At the heart of information processing, learning, and storing of information is the human's short-term memory (STM) system (Atkinson and Shiffrin, 1980). STM processes are under the immediate control of the individual and govern the flow of information in the memory system. Moreover, the processes carried out in STM can be called into action at the individual's discretion, with far-reaching consequences for performance (Atkinson and Shiffrin, 1980). Short-term memory is, though, an ephemeral storage system with the capacity to store a limited amount of information for a limited length of time. The capacity of STM is generally taken to be seven items, plus or minus two (Miller, 1956; Simon, 1981). What constitutes an item, or "chunk", of information is still somewhat ill-defined, but it might best be characterized as any piece of

information that is represented as a single, meaningful item or that has some unitary representation in long-term store (Loftus and Loftus, 1976). A chunk of information might include a single letter or number, a word, a group of words (a phrase), or even a sentence, concept, or idea. Thus, several such large chunks could be stored in STM, allowing an individual to follow a conversation, line of reasoning, or inductive process. Obviously, as a consequence of chunking an individual would be able to vastly increase his STM capability by judiciously recoding many low-information chunks into fewer high-information chunks (Loftus and Loftus, 1976).

Once entered, information in STM will remain only for a brief time, say 30 seconds, unless rehearsal (or some other process) occurs to maintain it. Information lost from STM cannot thereafter be recovered from it. It also appears that the processing of information in STM is serial and, as such, requires that different tasks be run on a time-shared basis. Work by Sternberg (1969) shows that, on the average, humans can perform an exhaustive search of STM in about 40 milliseconds. He also points out that all searches are exhaustive, regardless of where the desired item is found in the serial search.

3.3.2 Long-Term Memory

For new information to enter the relatively permanent long-term memory (LTM) that information must undergo elaborative rehearsal. Elaborative rehearsal entails taking information and creating elaborate codes (e.g., associative codes, imaginal codes, organizational codes) that are stable and later retrievable from long-term store (Loftus and Loftus, 1976). Klatzky (1980) terms such elaborative rehearsal "mental work."

LTM holds knowledge acquired through learning and experience; it is our knowledge base. Moreover, much of the information stored in LTM is encoded by meaning either in the form of imagery coding or semantic coding (Crider et al., 1983). An individual does not store a sentence verbatim; instead, only the underlying concept or meaning, or a mental image representing the same, seems to be retained. The organization of the knowledge base consists of information items that are highly structured and highly interlinked in relation to both time and relevance to each other. This organization is highly specific to the individual and the kinds of experiences he has encountered. The informational demands of any situation interact with this LTM organization. In certain situations information may be constrained or even actively inhibited. Moreover, humans are not unbiased, neutral observers (Rasmussen, 1980). Biases, attitudes, and expectancies will all play a part in how information is organized in LTM, what information will quickly be available, and what will be passed over or inhibited.

3.3.3 Stress

Another process that impacts human information processing, hypothesis formation, and option selection is stress. Stress is an inherent property in many human endeavors. It is an inevitable part of problem solving and decision making, and especially of dealing with uncertainty (Crider et al., 1983). When stress becomes excessive, the individuals involved may experience disrupted emotional, cognitive, and physiological functioning. High stress can exact its toll on all forms of human behavior, but for our purposes the primary concern is with stress-induced decrements to cognitive functioning.

Three models have been advanced for the study and understanding of stress and its effects. These paradigms are (after Crider et al., 1983):

(1) The response-based paradigm, which views stress as a cluster of disturbing physiological and psychological responses to difficult situations. Central to this paradigm is that different environmental events, known as stressors, can produce the same stress-response syndrome.

(2) The stimulus-based paradigm, which concentrates on the nature of stressful stimuli, thus viewing stress in terms of the environmental events or stimuli that cause such responses. This paradigm identifies three important characteristics of stressful stimuli: overload, conflict, and uncontrollability.

(3) The interactional paradigm, which builds on the contributions of the other two and augments them with information about the individual's motives and coping skills. Stress will occur, according to this paradigm, when the individual perceives a threat to important needs and motives, and when a person is unable to cope with the stressor. Thus, this paradigm views stress as an imbalance between individual needs and abilities and environmental demands.

It is the interactional and stimulus-based paradigms that are most germane to modeling the ASW task. The stimulus-based paradigm is most relevant to information input uncertainty and to the potential consequences associated with alternative actions in ASW situations, while the interactional paradigm can be useful in examining situations where commanders must react to high threats with limited resources.

As represented by the stimulus-based paradigm, stress is intimately involved with workload. Stimuli that become so intense that we can no longer adapt to them produce overload. One common form of overload is work overload. Ivancevich and Matteson (1980) address two forms of work overload: (1) when there are too many things to do in too little time and (2) when performance standards are so high that the work cannot be satisfactorily completed regardless of the time allowed. The ambiguity of conflict situations, that is, not knowing which alternative to choose, and the frustration related to situations viewed as uncontrollable are also stress inducing according to this paradigm.

The threat that certain elements in the environment pose to an individual commander's ambitions, responsibilities, and life and his ability to cope with these stressful situations are addressed by the interactional paradigm. Stress will be high when stressor demands exceed coping skills and low when coping skills more closely match stressor demands.

Most people suffer varying amounts of physiological, emotional, and cognitive disruptions under stress. It is the disruption to such cognitive functions as thinking, mental images, concentration, and memory that are deemed most important to the ASW problem. Normally, in nonstressful conditions thinking can be characterized as rational, logical, and flexible. But under stress our ability to organize our thoughts in a logical and coherent way is impaired (Crider et al., 1983). Our thinking instead tends to be obsessive and dominated by worries about the consequences of our actions and by negative self-evaluations. Images of personal inadequacies also dominate a person's consciousness at this time.

The ability to concentrate, that is, attend to specific stimuli while ignoring other task-irrelevant stimuli, is lessened under stress. The person

tends towards hypervigilance (Janis and Mann, 1977), easily disturbed by external stimuli and distracted by obsessive thoughts. With increased stress the individual may become "jumpy", i.e., overreactive to each new data input. The person's performance and decision making ability become increasingly impaired by the loss of concentration. Memory is also adversely affected. Apparently, stress disrupts the rehearsal process necessary to transfer information from STM to LTM, leading to frequent confusion about the sequence of events and other memory losses (Rimm and Somerville, 1977; Crider et al., 1983).

According to the extensive literature on the subject of stress, it appears that problem solving and decision making, which require a combination of good concentration, flexible thinking, intact memory, and visual imaging, can be significantly impaired by stress. We assume, therefore, that stress can disrupt a commander's cognitive functioning. Specifically, we assume that commanders may become increasingly suboptimal in their thinking, problem solving, and decision making behavior (Serfaty et al., 1983). Disruptions to concentration and memory functions will (severely) limit planning horizons. Besides satisficing, a commander's decision behavior may become characterized by less flexible, more regressive thinking, greater dependency on established biases and proclivities, and greater insensitivity to situational cues.

As a summary statement, it is useful to consider the effects of stress in the context of Wohl's (1981) SHOR paradigm described earlier in this report. If human perceptual and motor processes tend to escape the effects of stress, then these effects should have their greatest impact on the hypothesis (H) and option (O) generation and evaluation activities involved in ASW situation assessment and action selection.

One final point should be made. It is possible, through extensive training employing many scenarios (e.g., as practiced by astronauts with respect to emergency procedures), to achieve a reduction in the effects of stress on performance. Such training is designed to develop a rich repertoire of coping skills to assure the astronaut will be equal to any of the demands of space flight. In a difficult situation their approach is to pause, assess the situation, decide on a course of action, and then follow through on it (Crider et al., 1983).

The current type and level of training available for ASWCs (e.g., one course at the Fleet ASW School in Norfolk, Virginia) and the nature of the job itself make it unlikely that an ASWC would even approach anything like the degree of training exhibited by astronauts when carrying out their emergency procedures. Hence, it is likely that stress will indeed tend to have a limiting effect on an ASWC's hypothesis and option generation and evaluation activities.

3.3.4 Thresholds for Action

The last of the cognitive issues deals with thresholds for action. At what point is an ASWC moved to act? What appear to be some of the variables involved? Not all changes in a stimulus induce a change in action or, for that matter, are even perceived. Perception of a change, however, might be a necessary, if not sufficient, condition to trigger action. At the basic physiological level, detection is in terms of the absolute threshold or minimum quantity of stimulation necessary to produce a sensation. Contrary to long-held beliefs, research has revealed that the absolute threshold is not a constant value, but is influenced by the number of competing sensations at the time, experience with that class of sensations, and motivation (Houston et

al., 1979). Thus, the absolute threshold of detection changes from person to person and from situation to situation (Crider et al., 1983).

Rarely is an ASW commander confronted with a problem concerning the absolute threshold of detection. His sonar staff may be faced with such problems, but more often the ASWC's problem is one of discrimination: deciding when two stimuli or sets of data are sufficiently different or detecting when a particular stimulus or data set has changed. In detection thresholds, the minimum amount of stimulus change that is necessary for a difference to be detected is referred to as the difference threshold and is defined as the level of difference that is detected 50% of the time (Houston et al., 1979). This minimum difference is often called the just-noticeable difference.

Like the absolute threshold, the difference threshold is not a constant. It was E.H. Weber in 1834 (Houston et al., 1979) who first observed that the amount of change in a stimulus that is detectable as different is proportional to the intensity of the stimulus. The formulation of this relationship into a general law was done by G. Fechner, who called the relationship Weber's Law (Crider et al., 1983). The law is defined as $\Delta I/I=k$, where I is the size of the reference stimulus, ΔI is the size of the difference necessary to be noticed, and k is the resulting constant of proportionality. The constant of proportionality varies for different sense modalities.

Based on recent work by Tversky and Kahneman (1984) on mental accounting, it appears possible to describe a commander's threshold for action in terms similar to Weber's law. Commanders over time gather information, make judgments, and choose response options. Throughout, they are performing some kind of mental accounting, similar to that described by Tversky and Kahneman, to

decide when some variable such as system cost or situational uncertainty has changed sufficiently to warrant action. The argument thus shifts from the minimum detectable change of Weber's law to the concept of the minimum change in a situational variable such as cost, risk, or uncertainty. Based on this relatively recent result, the notion of a threshold for action appears to be an appropriate construct to consider in modeling an ASWC's decision processes.

3.4 PERSPECTIVE ON THE ASWC SIMULATION MODEL

A host of behavioral and cognitive issues that appear to be relevant to the ASW decision task have been identified. Only a small subset of these descriptive considerations are, however, encoded in the existing ASWC model.

In particular, the ASWC model represents two types of imperfect information processing behavior: primacy/recency effects (Lopes, 1982) and miscalibration of assessed probabilities (Lichtenstein et al., 1982). Limited memory capacity, threat-sensitive choice-making strategies, and action thresholds are also accommodated in the existing model. These considerations are addressed primarily because they: (1) are germane to the specific ASW decision problem that is modeled and (2) dovetail with the normative models selected to represent the ASWC's decision process.

The structure of the next chapter is as follows. For each cognitive activity, situation assessment and resource allocation, the normative model is presented and then the descriptive constraints or elements encoded for that activity are presented.

SECTION 4

MATHEMATICAL FORMULATION OF THE ASW DECISION MODEL

4.1 INTRODUCTION

The mathematical model encoded in the ASW simulation addresses a special case of the ASW problem and decision process as delineated in Section 2. The setting is as follows. The battle group is operating in an ocean area where convergence zone propagation paths exist. The EMCON policy dictates that only passive sonar be used in ASW search. All subsurface contact data are confirmed (no false alarms) and are reported directly to the ASWC. The tactical decisions are the air ASW missions. ACCON policy modifications, evasive steering, and surface platform repositioning decisions are not modeled. Furthermore, a centralized command structure is imposed. That is, all decisions concerning the allocation of aircraft (carrier and surface platform based) are made by the ASWC. These include: (1) which aircraft to send, (2) the aircraft's destination, (3) what sonobuoy maneuver the aircraft is to employ, and (4) the sonobuoy spacing.

It is expected that an ambush on a carrier will involve more than one submarine at the same time (Dunnigan, 1982). Thus, the ASWC is receiving multiple-source contact data from a set of geographically distributed sensors. It is his duty to perform the multi-sensor/multi-source data correlation. The allocations of aircraft are made on the basis of the data correlation procedure. The cognitive activities of the ASWC are thereby conceptualized as a cascading of two activities: situation assessment and resource management.

The ASW simulation model is time-based and it is comprised of three modules as diagrammed in Fig. 4-1. The fundamental pre-engagement inputs to the environmental driver are trajectories of the enemy submarines, own-force composition and trajectory, and own-force platform patrol procedures. Upon the initial detection of a submarine, the inputs to the environmental driver are the tactical commands issued by the ASWC. The purpose of the environmental driver is to update the states of own-force platforms and enemy submarines, and to generate submarine contacts from own-force sensors. The situation assessor performs the multi-sensor data correlation, or multi-target tracking, with these contact data. The outputs of the situation assessor are a set of target tracks and their respective state estimates and error covariances. The decisions to allocate aircraft for contact prosecution or target localization are made in the resource manager. The necessary inputs are own-force state estimates and the outputs of the situation assessor. The aircraft allocation decisions are input then to the environmental driver and the cycle begins anew.

The remaining subsections describe the functional mathematical representations of the three major modules. The discussions of the human decision making modules (situation assessor and resource manager) are outlined as follows. First, normative models of the commander's cognitive activities are described. Second, the descriptive limitations and biases, selected from those discussed in Section 3, used to constrain or perturb the normative models to reflect more human-like behavior are presented.

4.2 ENVIRONMENTAL DRIVER

The purpose of the environmental driver is to update own-force and enemy platform states, and to generate the sonar contact data necessary for target

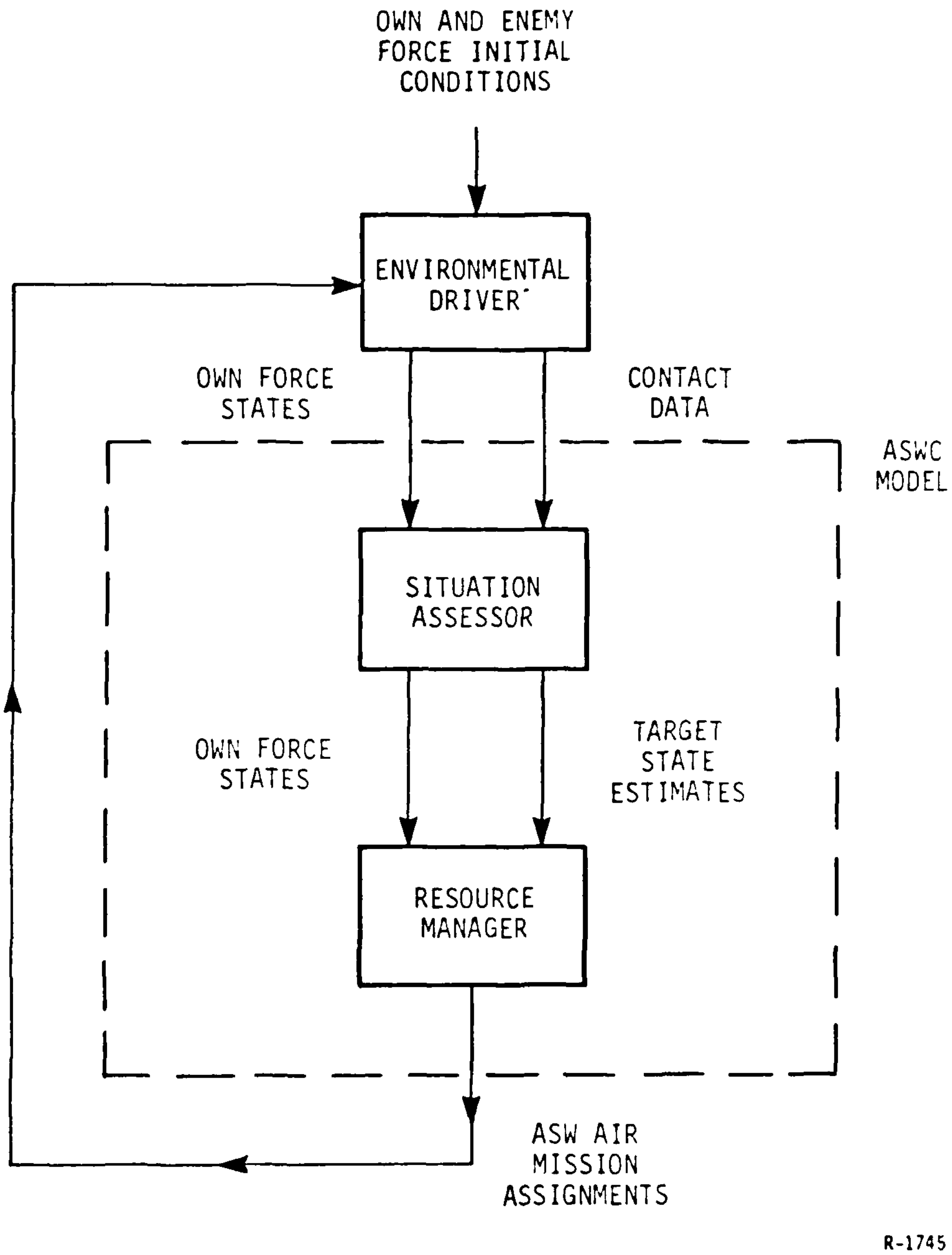


Figure 4-1. ASWC Model and Environmental Driver

tracking. The remainder of the subsection describes the mathematical formulation of the ASW environment and contact generation.

4.2.1 ASW State Space

The ASW state space, Z, is defined to be the union of the states of: (1) own-force surface and subsurface platforms S, (2) enemy submarines E, (3) ASW aircraft A, and (4) ASW sonobuoys B. That is,

$$Z = \{S,E,A,B\}.$$

The state S_i of own-force surface or subsurface platform i is given by a Cartesian product of six sets:

$$S_i = \{S_i : S_i = (px_i, py_i, v_i, \theta_i, pt_i, nz_i)\} ,$$

where

$PX = \{px : px \; \varepsilon(-\infty,\infty)\}$ is the set of horizontal coordinates [nm] ,

$PY = \{py : py \; \varepsilon(-\infty,\infty)\}$ is the set of vertical coordinates [nm] ,

$V = \{v : v \; \varepsilon[0,\infty)\}$ is the set of operating speeds [nm/hr] ,

$\Theta = \{\theta : \theta \; \varepsilon[0,360)\}$ is the set of platform headings [degrees] ,

$PT = \{pt : pt =$ none, hull-mounted, TACTAS, sonobuoy$\}$ is the set of passive sonar types,

$NZ = \{nz : nz = 0,1,2,3\}$ is the set describing the range of the sonar in convergence zones.

$S = \bigcup_{i=1}^{N_s} S_i$ is the set describing the states of all $(i=1,\ldots,N_s)$ of all the own-force surface and subsurface platforms.

The state E_i of enemy submarine i is given by:

$$E_i = \{E_i : E_i = (px_i, py_i, v_i, \theta_i)\} .$$

$E = \bigcup_{i=1}^{N_e} E_i$ is the set describing the states of all $(i=1,\ldots,N_e)$ the enemy submarines.

The state A_i of aircraft i (rotary- or fixed-wing) is given by a Cartesian product of nine sets:

$$A_i = \{A_i : A_i = (px_i, py_i, v_i, \theta_i, te_i, td_i, t\ell_i, m_i, nb_i)\},$$

where

$TE = \{te : te \; \varepsilon [0,\infty)\}$ is the set of endurance times, or flight time available [hr],

$TD = \{td : td \; \varepsilon [0,\infty)\}$ is the set of dispatch times [hr],

$TL = \{t\ell : t\ell \; \varepsilon [0,\infty)\}$ is the set of times late to datum [hr],

$M = \{m : m =$ maneuver 1, maneuver 2, maneuver 3$\}$ is the set of sonobuoy maneuvers,

$NB = \{nb : nb \; \varepsilon \; I^+\}$ is the set describing the number of sonobuoys available.

$A = \bigcup_{i=1}^{N_a} A_i$ is the set describing the states of all $(i=1,\ldots,N_a)$ the ASW aircraft.

Note that the aircraft altitudes and submarine depths are not included in their respective state spaces.

The state B_i of sonobuoy i is given by a Cartesian product of four sets:

$$B_i = \{B_i : B_i = (px_i, py_i, nz_i, o_i)\},$$

where

$O = \{o : o =$ on, off$\}$ is the set describing the sensing status of a sonobuoy,

$B = \bigcup_{i=1}^{N_b} B_i$ is the set describing the state of all $(i=1,\ldots,N_b)$ the sonobuoys.

4.2.2 ASW Principal State Transitions

The Cartesian motion of any surface, subsurface, or air platform i, over a discrete time interval Δt, is given by

$$px_i(t+\Delta t) = px_i(t) + \Delta t\ v_i(t) \cos \theta_i(t) ,$$

$$py_i(t+\Delta t) = py_i(t) + \Delta t\ v_i(t) \sin \theta_i(t) .$$

The sensing status of sonobuoy i is determined as follows. A sonobuoy is considered on at time t only when there is an ASW aircraft $a_j \varepsilon A$ within monitoring distance dm_j to process its signals or to relay the signals to a surface ship. Mathematically,

$$o_i(t) = \begin{cases} \text{on} & \text{if there exists } a_j \varepsilon A : d_{ij}(t) < dm_j , \\ \text{off} & \text{otherwise} , \end{cases}$$

where d_{ij} is given by the equation

$$d_{ij}(t) = \sqrt{\left(px_i(t) - px_j(t)\right)^2 + \left(py_i(t) - py_j(t)\right)^2} .$$

4.2.3 ASW Contact Generation

An ASW passive contact c between platform j and submarine k is a four-tuple $c=(j,pt,t,\hat{\theta}_{jk})$, where $t \varepsilon T$ is the time of contact [hr] and $\hat{\theta}_{jk} \varepsilon \Theta$ is the bearing [degrees] from sonar to contact. $\hat{\theta}_{jk}$ is given by the equation

$$\hat{\theta}_{jk} = \tan^{-1} \left[\frac{py_k(t)-py_j(t)}{px_k(t)-px_j(t)} \right] + \varepsilon_j .$$

ε_j is a zero-mean normal random variate whose standard deviation $\sigma_{\varepsilon j}$ is a function of the sonar type pt. Note that

$$j \ \varepsilon \begin{cases} B & \text{if pt = sonobuoy,} \\ S & \text{otherwise.} \end{cases}$$

Four conditions determine whether or not a surface or subsurface platform s_j passively detects enemy submarine e_k. First, the platform s_j must reside in one of the convergence zones about the submarine as shown in Fig. 4-2. That is, a contact is possible if the distance between s_j and e_k, d_{jk}, lies in one of the intervals defined below:

$$d_{jk} \in \left[czr(i),\ czr(i) + czw(i)\right] \ ,\ i=1,\ldots,nz_j \ .$$

czr(i) is the range to convergence zone i and czw (i) is the width of convergence zone i. These ranges and widths are depicted in Fig. 4-3. Second, the contact must lie in the coverage sector of the sonar. As described in Section 2, hull-mounted and TACTAS sonars have gaps in their coverage. Contacts with values of $\hat{\theta}$ that violate this sensor constraint are disallowed. Third, a contact is valid if there does not exist another platform $s_\ell \varepsilon S$ such that

$$d_{j\ell} \in \left[czr(i),\ czr(i) + czw(i)\right],\ i=1,\ldots,nz_j,$$

and

$$\hat{\theta}_{j\ell} \in \left[\hat{\theta}_{jk} - \sigma_{\varepsilon j},\ \hat{\theta}_{jk} + \sigma_{\varepsilon j}\right].$$

This demands the absence of interference caused by the presence of own-force platforms operating along the same bearing as the contact $\hat{\theta}_{jk}$. Fourth, the maximum range of a sonar nz is not to be construed as the range at which the probability of detection is unity, but simply the range at which detection is possible. This uncertainty stems from crude sonar performance predictions, imperfect sonar hardware, and nonoptimal sonar operators. Both the hull-mounted and TACTAS sonars are assigned an expected probability of detection

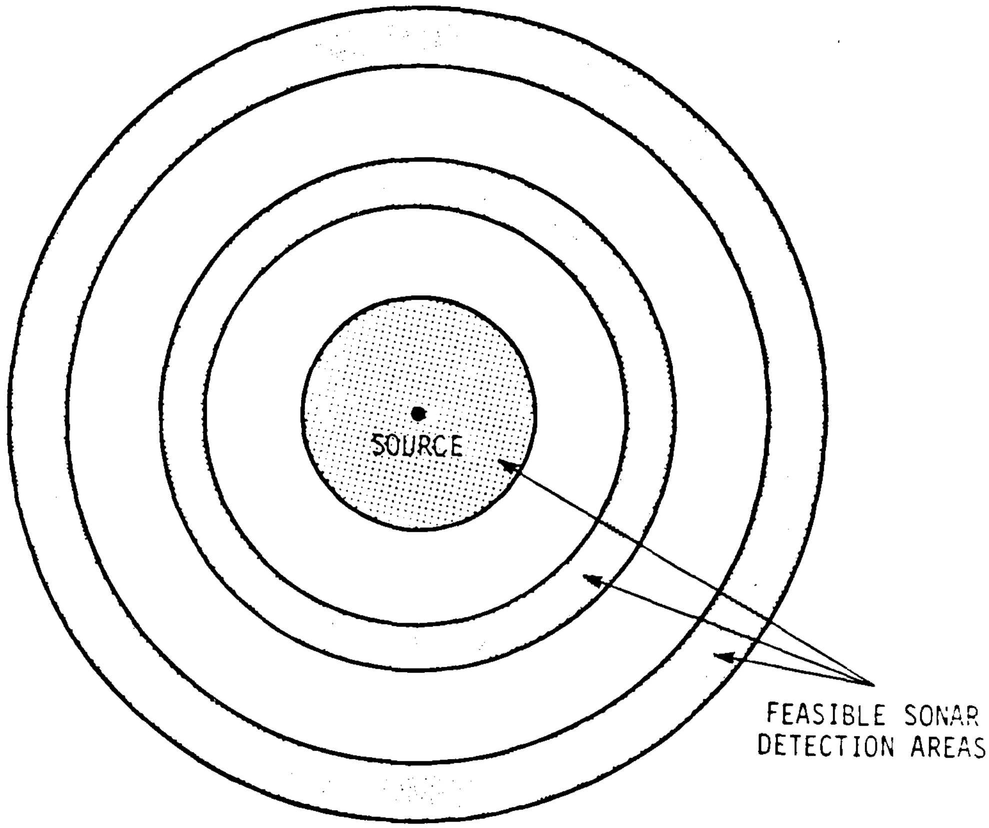
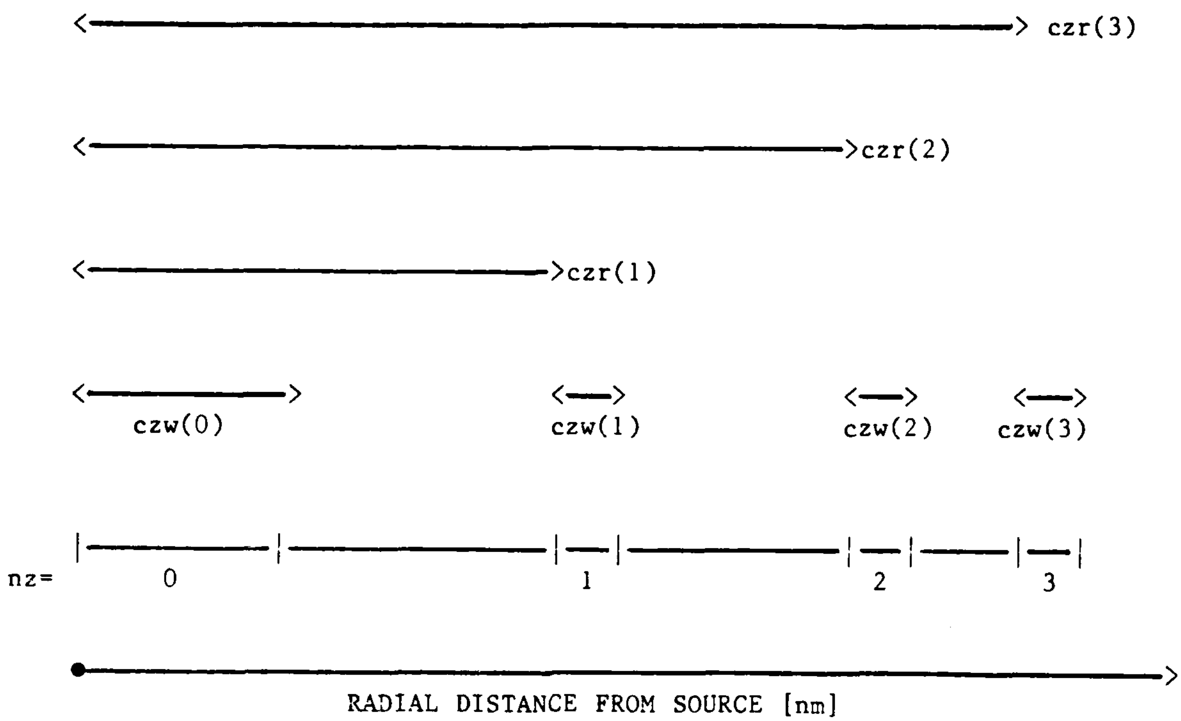


Figure 4-2. Plan View of Convergence Zones



LEGEND:

nz = CONVERGENCE ZONE

czr(i) = RANGE TO CONVERGENCE ZONE i [nm]

czw(i) = WIDTH OF CONVERGENCE ZONE i [nm]

Figure 4-3. Cross-Sectional View of Convergence Zones

for each zone $p(\cdot|nz_i)$ given the presence of a submarine in zone nz_i as shown in Fig. 4-4. Thus a contact is generated when the first three conditions are satisfied and when a uniform random variate $u \in [0,1] < p(\cdot|nz^*)$, where nz^* denotes the actual zonal location of the sensor relative to the submarine.

Only the first and fourth conditions apply for the DIFAR sonobuoys. However, the probability of detection in the sonobuoy's direct path, $p(\cdot|nz=0)$, is not uniform over the range of a zone, but is given by the standard exponential model for detection equipment (Kimball and Morse, 1950),

$$p(d_{ij}|nz=0) = e^{-d_{ij}/k} \quad ,$$

where d_{ij} is the distance between sonobuoy i and submarine j. Assuming that the probability of detecting a submarine on the edge of the direct-path zone is 0.5 $\left(d_{ij} = czw(0)\right)$, then it follows that k is given by

$$k = \frac{czw(0)}{0.693} \quad .$$

The graph of the probability of detection versus range to target in Fig. 4-5 is often called the lateral range curve (U.S. Naval Academy, 1977). Convergence zone detections are not considered for sonobuoys; thus for sonobuoy b_j, $p_j(\cdot|nz)$ is abbreviated $p_j(\cdot)$.

4.3 SITUATION ASSESSOR

The purpose of the ASW situation assessor is to transform imperfect contact data on multiple submarines from distributed sensors into coherent state estimates of the submarines: namely, positions and velocities. This procedure is comprised of two activities:

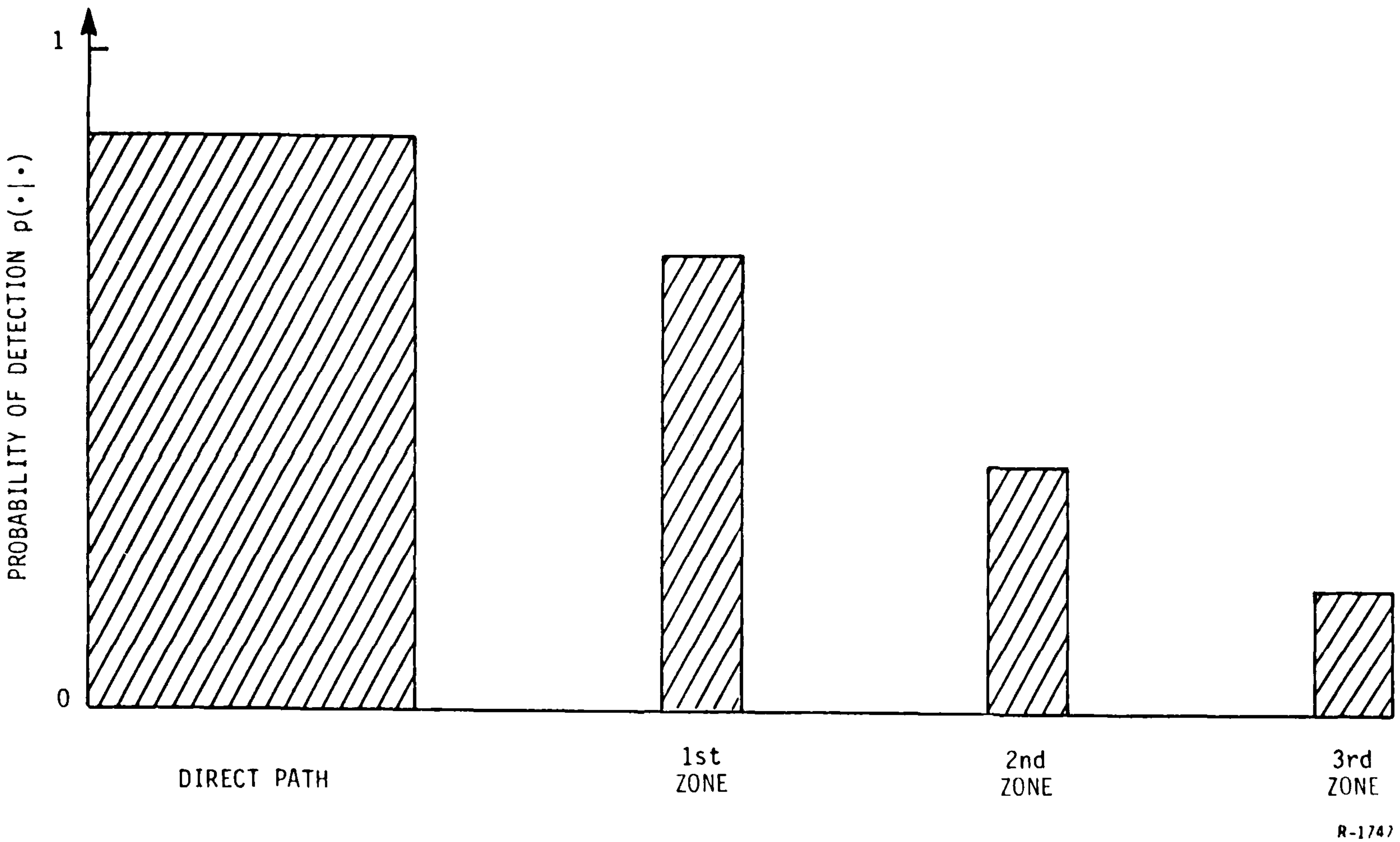
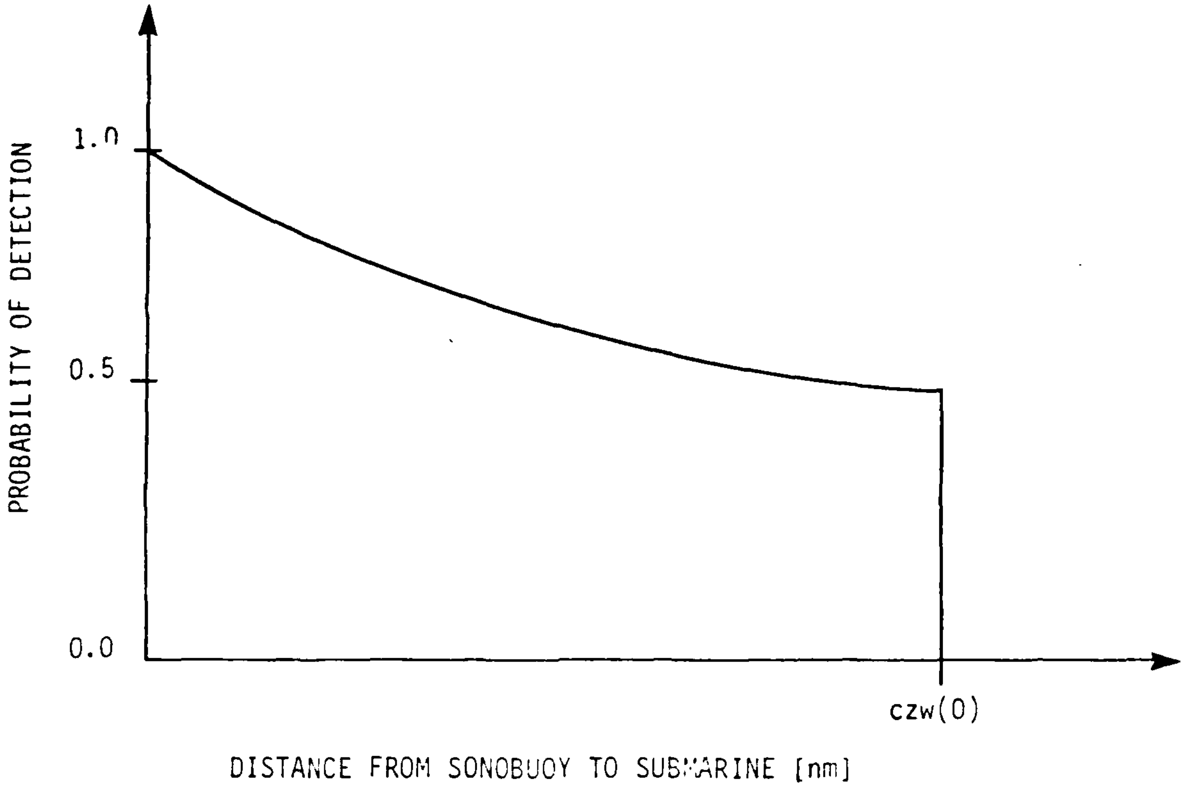


Figure 4-4. Sonar Probability of Detection Profile in a Convergence-Zone Environment



R-1743

LEGEND:

czw(0) = DIRECT PATH RANGE [nm]

Fig. 4-5. Lateral Range Curve for a DIFAR Sonobuoy

1. To correlate sensor measurements (contact data) with individual submarines (data association).

2. To update the state estimates of the submarines on the basis of the data associations, prior state estimates, and known dynamics of submarine motion (state estimation).

Herein, the contact data are assumed to be uncorrelated and corrupted by noise. False detections, or alarms, are not considered; all contacts are valid. The passive sensors provide only bearing information on the target. This state estimation problem, for one sensor and one target, is termed two-dimensional, bearings-only target motion analysis (TMA) (Petridis, 1981; Aidala and Himmel, 1983; Wilhoit, 1983). The prevalent technique for solving this problem is Kalman filtering. However, there exists no simple, or uniquely prominent, formulation since the bearing measurement and target maneuvers introduce nonlinearities into the system.

The Kalman filter is a natural choice, then, as a normative framework for the ASWC's state estimation problem. It is chosen not only because it is the primary TMA technique, but also because it has been successfully used to model human manual control (Kleinman et al., 1971), human display monitoring (Kleinman and Curry, 1977), and an anti-aircraft artillery dynamic decision task (Pattipati et al., 1983). The formulation of the state estimation Kalman filter is not meant to advance the TMA technology, but to present a normative framework that solves the problem in a human-like fashion and lends itself to normative-descriptive modeling.

The normative formulation of the data association procedure follows closely the work of Singer et al. (1974). The logic for initiating and deleting possible tracks is similar to the approach outlined by Reid (1979).

4.3.1 General Filter Formulation

The motion of a submarine being tracked is modeled by the state equation

$$x(t+1) = \Phi(t)\; x(t) + G\; u(t),$$

where $x(t)$ is the $(n\times 1)$ state vector of the submarine at time t, $\Phi(t)$ is the $(n\times n)$ state transition matrix, G is the $(n\times \ell)$ zero mean, white Gaussian noise vector with covariance $Q(t)$. $u(t)$ accounts for the errors in the state space model.

The sonar contact data are described by the observation equation

$$y(t) = H(t)x(t) + v(t),$$

where $y(t)$ is the $(m\times 1)$ vector of sonar measurements, $H(t)$ is the $(m\times n)$ measurement matrix, and $v(t)$ is an $(m\times 1)$ zero mean, white Gaussian noise vector with covariance $R(t)$. $v(t)$ accounts for the errors associated with the measurement data.

The objective is to derive an estimate of the state of the submarine $\hat{x}(t)$, and the error covariance in the estimate $P(t)$, on the basis of the observation $y(t)$. The normative method for solving such problems is the discrete Kalman filter (Gelb, 1974). The best (unbiased, minimum variance) estimate of the state of the submarine at time t, given all the measurements up to and including $y(t)$, is termed $x(t|t)$. This estimate is given by the equation (Gelb, 1974)

$$\hat{x}(t|t) \;=\; \hat{x}(t|t-1) + K(t)\;\left[y(t) - H(t)\;\hat{x}(t|t-1)\right],$$

where

$$\hat{x}(t+1|t) = \Phi(t)\ \hat{x}(t|t),$$

$$P(t+1|t) = \Phi(t)P(t|t)\ \Phi^T(t) + GQ(t)G^T,$$

$$K(t) = P(t|t-1)\ H^T(t)\ \left[H(t)\ P(t|t-1)H^T(t) + R(t)\right]^{-1},$$

$$P(t|t) = \left[I-K(t)H(t)\right]P(t|t-1).$$

When no measurements are available, the states and their estimation error covariances are propagated using the equations for $\hat{x}(t+1|t)$ and $P(t+1|t)$. These are termed the time-update equations.

The efficacy of the state estimation is determined by examining the difference between the actual measurement $y(t)$ and the predicted measurement $\hat{y}(t|t-1)$. This difference is called a residual $\delta(t)$. The residual is given by the equation

$$\delta(t) = y(t) - \hat{y}(t|t-1) = y(t) - H(t)\ \Phi(t-1)\ \hat{x}(t-1|t-1),$$

or

$$\delta(t) = y(t) - H(t)\ \hat{x}(t|t-1).$$

The covariance of the residuals $B(t)$ is

$$B(t) = E\left[\delta(t)\delta(t)^T\right] = H(t)\ P(t|t-1)\ H^T(t) + R(t) \quad .$$

4.3.2 Bearings-Only Filter Formulation

The state of a submarine is given by its Cartesian position and velocity, i.e.,

$$x = \begin{bmatrix} px \\ py \\ vx \\ vy \end{bmatrix}.$$

The equations of submarine motion assuming constant target velocity are:

$$px(t+\Delta t) = px(t) + vx(t)\ \Delta t,$$

$$py(t+\Delta t) = py(t) + vy(t)\ \Delta t,$$

$$vx(t+\Delta t) = vx(t),$$

$$vy(t+\Delta t) = vy(t).$$

Thus, the state transition matrix is defined as

$$\Phi(t) = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} .$$

The error u(t) is incorporated into the model to account for the submarine's ability to change course or speed (maneuver). Its covariance Q(t) is then equal to the maneuver variance, σ_V^2 [nm^2/hr^2], and the disturbance matrix is defined as

$$G = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix} .$$

The geometry of a passive, bearings-only measurement is shown in Fig. 4-6. There exist two general formulations of the measurement equation for a bearings-only TMA problem under convergence zone conditions. The first formulation assumes that a bearing measurement can be constructed as a bearing/range measurement with large uncertainty in the range (Bossard and Graves, 1980). Using the notation from Fig. 4-6, the measurement vector y is defined by

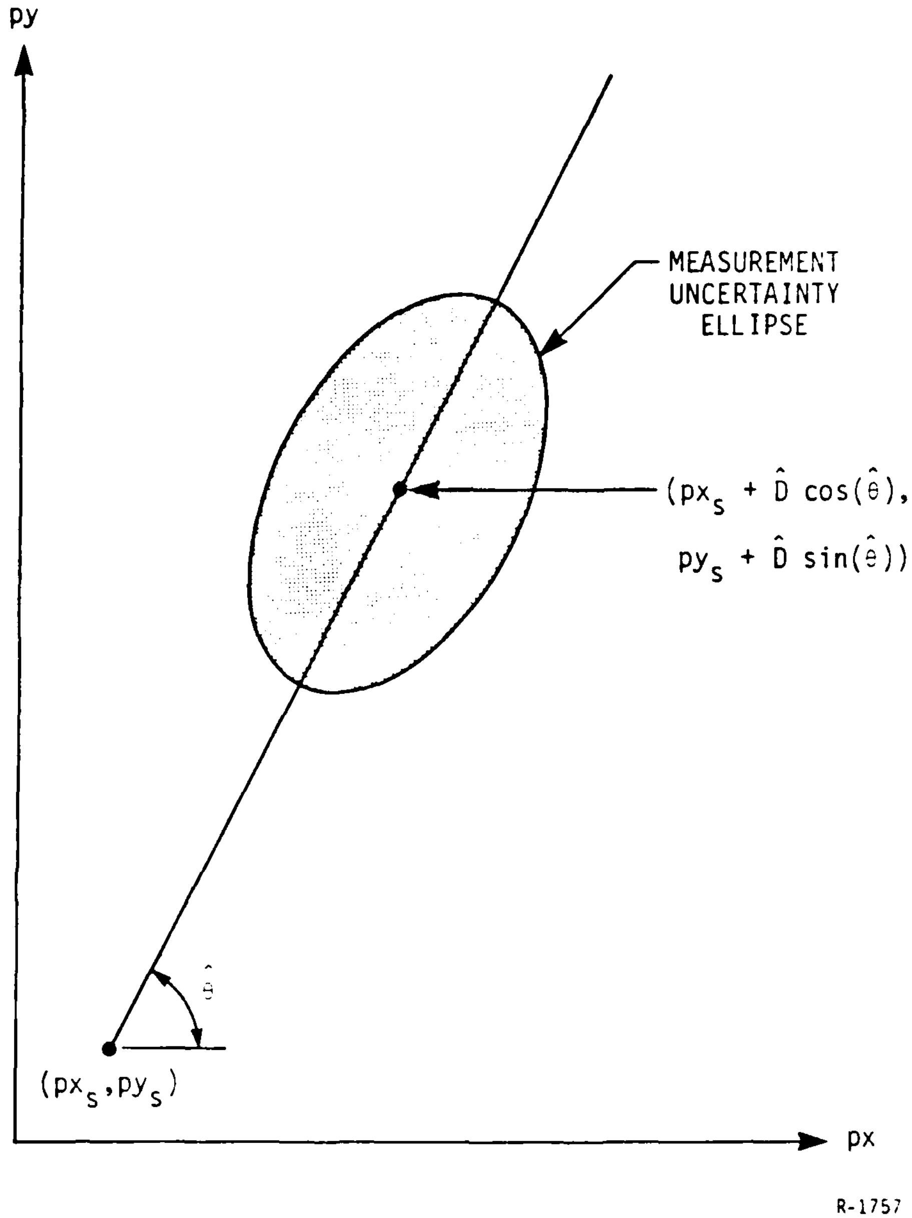


Figure 4-6. Geometry of the Uncertainty Ellipse about a Bearing/Range Measurement

$$y = \begin{bmatrix} px_i + \hat{D}\cos(\hat{\theta}) \\ py_i + \hat{D}\sin(\hat{\theta}) \end{bmatrix},$$

where $\hat{D}$ is the expected range to the target, or mean detection range[nm]. The measurement matrix H is defined as follows:

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}.$$

The measurement error covariance R on a bearing/range measurement is deemed highly elliptic. This uncertainty ellipse is depicted in Fig. 4-6. Mathematically, this state-dependent covariance R is described by:

$$R = \begin{bmatrix} \overline{d(px_j)^2} & \overline{d(px_j)\,d(py_j)} \\ \overline{d(px_j)d(py_j)} & \overline{d(py_j)^2} \end{bmatrix}.$$

The variations in the target j's state estimates are

$$d(px_j) = d\hat{D}\cos(\hat{\theta}) - \hat{D}\sin(\hat{\theta})\,d\hat{\theta}$$

and

$$d(py_j) = d\hat{D}\sin(\hat{\theta}) + \hat{D}\cos(\hat{\theta})\,d\hat{\theta}\ .$$

$d\hat{D}$ is the error in the range estimate to the target, and $d\hat{\theta}$ is the bearing error in the measurement. Assuming that the range and bearing errors are uncorrelated,

$$\overline{d(px_j)d(py_j)} = \sin(\hat{\theta}) \cos(\hat{\theta})\left(\overline{d\hat{D}^2} - \hat{D}^2\, \overline{d\hat{\theta}^2}\right).$$

The existence of convergence zones is accounted for by allowing $\hat{D}$ and $d\hat{D}$ to be large. For this formulation of a bearings-only measurement, the existence of a target is hypothesized in one large area as shown in Figure 4-6.

The second formulation is analogous to the first except that the target is hypothesized to be in n small areas, where n is the number of convergence zones (note that n includes the direct-path zone) (Wihoit, 1983). Effectively, one bearings-only measurement is transformed into n possible position measurements. The expected range to a target in zone i is specified by

$$\hat{D}_i = czr(i) + \frac{czw(i)}{2},$$

and the range variance, assuming uniform error distribution, is

$\overline{d\hat{D}_i^2} = czw(i)^2/12.$

The first formulation is simple to implement, but is a gross approximation. The second formulation is more difficult to implement, but mimics well the environmental reality. In a single-source/multi-sensor scenario, it is clear that the second formulation would not be a cognitive burden to the commander. However, in a multi-source/multi-sensor scenario, the information processing burden would be too great for other than the first formulation. (This does not, however, preclude the use of the second formulation as the normative basis for the commander's situation assessment.) In the present simulation model the first formulation is used.

4.3.3 Data Association Algorithm

In an environment with multiple submarines and no false detections, there are 2^n-1 possible hypotheses about the origin of n measurements, or contacts. For example, after two sonar measurements the commander forms three hypotheses: (1) the source of the first contact contact is submarine a, (2) the source of the second contact is submarine b, and (3) one submarine is the source of both contacts. A third contact adds four more hypotheses, and so on.

The purpose of the data association algorithm is to prune the number of hypotheses, or tracks, by associating measurements to an appropriate subset of the existing set of tracks. The appropriateness of an association is outlined below.

Let $\Omega(t)$ be the set of possible tracks at time t after n measurements have been associated to tracks and the track state estimates have been updated. The number of elements in $\Omega(t)$ is denoted NH(t); NH(t) is bounded by 2^n-1. The i^{th} element (or track), $\omega_i(t)$, is defined as follows:

$$\omega_i(t) = \left(\hat{x}_i(t|t-1),\ P_i(t|t-1)\right).$$

Upon receipt of the nth measurement y^n, the commander must decide either to associate the contact data with one or more of the existing hypotheses, or to initiate a new hypothesis. The classical normative procedure for making this judgment is as follows. The measurement y^n is associated with track i when the normalized square of its residual is smaller than some value η^2. (Singer et al., 1974). Mathematically, $(y^n-y_i)^T B_i^{-1} (y^n-y_i) < \eta^2$ for an association between measurement y^n and track ω_i. The measurement space region defined by the above inequality is termed a gate. Since the covariance of the

residuals B_i is a function of the covariance of the estimation error P_i and the residuals are weighted by B_i, the gate criterion demands that the statistical distance between the actual measurement and the predicted measurement be negligible for tracks that are well established (small estimation error covariances). Conversely, larger residuals are allowed for newly established tracks that typically have larger error covariances. The gate value is directly translatable to an allowable missassociation probability.

When there are no tracks in the set Ω^n that satisfy the gate criterion, then and only then is a new track initiated using the measurement y^n. The initial condition estimation error covariance P_j is specified by:

$$P_j(0|0) = \begin{bmatrix} \sigma_p^2 & 0 & 0 & 0 \\ 0 & \sigma_p^2 & 0 & 0 \\ 0 & 0 & \sigma_v^2 & 0 \\ 0 & 0 & 0 & \sigma_v^2 \end{bmatrix} .$$

The initial position error estimation variance σ_p^2 and velocity estimation error variance σ_v^2 are chosen to be very large. Effectively, no prior information is assumed. Thus, the position estimates approximately coincide with the measurement and the velocity estimates remain at zero after the track is updated.

In the case where ℓ measurements are associated with track i at one time t, the measurement update equation for the final ℓ-1 measurement associations are:

$$\hat{x}_i^j(t|t) = \hat{x}_i'(t|t) + K_i^j(t) \left[y^j(t) - H(t)\, \hat{x}_i'(t|t)\right],$$

$$K_i^j(t) = P_i'(t|t)\, H^T(t) \left[H(t)\, P_i'(t|t)\, H^T(t) + R(t)\right]^{-1},$$

$$P_i^j(t|t) = \left[I-K^j(t)\,H(t)\right] P_i'(t|t),$$

where $j=2,\ldots,\ell$, and the prime stands for $(j-1)$ and denotes a quantity after the association of measurement j-1 after a track has been updated by a measurement at time t. Its residual with any other measurement received at the same time is

$$\delta_i(t) = y(t) - H(t)\,\hat{x}_i(t|t).$$

The covariance of the residual is specified by the equation

$$B_i(t) = H(t)\,P_i(t|t)\,H^T(t) + R(t).$$

4.3.4 Descriptive Elements

The normative formulation of the situation assessment procedure in a dense multi-source/multi-sensor environment is undoubtedly beyond a human's cognitive capacity. Recall of position and velocity estimates and their estimation error covariances (uncertainty) is an arduous task for more than a few select hypotheses. This phenomenon can be attributed to the finite nature of the human's STM capacity (Miller, 1956; Simon, 1978).

Limited STM is represented in the ASWC model by constraining the possible number of hypotheses the ASWC can consider, at any one time, i.e.,

$$NH(t) \leq NH^* \text{ for all } t\epsilon T\ .$$

For the first n measurements,

$$n=\log_2 (NH^* + 1),$$

the situation assessment model forms NH^* hypotheses using the optimal procedure. Every measurement thereafter is associated either with an existing track, or set of tracks, using the gate criterion, or a new track is initiated. In the latter event, an existing track must be deleted to

accommodate the STM constraint. Tracks are deleted using one of two procedures. First, when two tracks ω_i and ω_j have overlapping position estimates they are merged into one track. This can be interpreted as a (track) indifference threshold. The state estimate of the merged track, x_{ij}, is specified by the equation (Reid, 1979):

$$\hat{x}_{ij} = \left(P_k^{-1} + P_j^{-1}\right)^{-1} \left(P_i^{-1}\hat{x}_i + P_j^{-1}\hat{x}_j\right).$$

The covariance P_{ij} of the merged track is

$$P_{ij} = \left(P_i^{-1} + P_j^{-1}\right)^{-1}.$$

Second, when the existing tracks have distinct position estimates, the track with the greatest position error covariances is struck from the admissible set Ω. This can be interpreted as a (position certainty) threshold for action.

The specific heuristics and biases an ASWC employs to process probabilistic information in the situation assessment activity are unknown. In fact, according to Einhorn (1980, p.4):

> ...it may be that heuristics such as representativeness, availability, anchoring and adjusting, are "metaheuristics" that is, they are rules on how to generate rules. Therefore, when confronted by problems that one has encountered before ... or problems whose specificity makes them seem novel, metaheuristics direct the way in which specific rules can be formed to solve the problem. The idea of a metaheuristic allows one to retain the generality that any rule necessarily implies, yet at the same time allows for the important effects of context, wording, response mode, and so on.

Moreover, Einhorn (1980) demonstrates that the same heuristic can induce different judgments. For these reasons, the descriptive elements do not mimic specific information processing heuristics and biases. Instead, a normative-descriptive approach is meant to produce a range of information processing behaviors. Normative-only models are not equipped with exogenous cognitive parameters; thus, human-like performance can only be obtained by perturbing

parameters and constructs that are indigenous to the normative models. On the other hand, descriptive-only models are not adaptive to a changing environment. A suboptimal information processing behavior is postulated at the beginning of the scenario and assumed constant throughout the scenario.

The ASW state estimation problem in situation assessment is clearly a cascaded inference problem (Schum, 1980). That is, current estimates of track states and their error covariances are a combination of the most recent imperfect measurements and uncertain estimates derived from past unreliable data. In these situations, humans tend to overestimate the contribution of the most recent predictions (Peterson, 1973) in marked contrast to the conservative judgmental behavior observed in single-stage inference (Slovic and Lichtenstein, 1971; Slovic et al., 1977). The heuristic devices that induce biased probabilistic inferences, or judgments, are discussed in Section 3.

The primacy/recency human probabilistic information processing phenomena observed by Lopes (1981; 1982), in particular, can be accounted for in the state estimation procedure by perturbing the filter's effective memory span. Present state estimates can be manipulated to depend more (or less) on the most recent measurements than what is optimally prescribed. It can be shown that the introduction of a large artificial driving noise covariance Q induces the filter to overweight the most recent data (Schweppe, 1973). Analogously, the introduction of excessive measurement error covariance R causes the filter to underweight the most recent data. For example, define a discrete, scalar system with no dynamics:

$$
\begin{aligned}
x(t+1) &= x(t) + u(t) \quad , \\
y(t+1) &= x(t+1) + v(t+1) \; .
\end{aligned}
$$

The covariances of the process noise u and measurement noise v are Q and R, respectively. The steady-state Kalman filter solution is given by:

$$\hat{x}(t+1) = \hat{x}(t) + K_\infty[y(t+1) - \hat{x}(t)],$$

where K_∞ denotes the steady-state Kalman gain. After deriving the steady-state error covariances it can be shown that

$$K_\infty = \frac{2}{1+\sqrt{1+\frac{4R}{Q}}}.$$

Thus, as Q approaches infinity, the gain or weight ascribed to the most recent measurements K_∞ approaches one. As R approaches infinity, the gain approaches zero. Note that in a dynamic system, K_∞ is driven by more than the process and measurement covariances.

Humans not only systematically bias probabilistic judgments, but they also "...ignore uncertainty and rely predominantly on habit or simple deterministic rules" (Slovic, 1982, p. 170). In the situation assessment model, this behavior is conceptualized as the ASWC's subjective interpretation of an objective uncertainty. The objective uncertainties in the ASW environment are the expected sensor bearing errors. The model allows for the ASWC to employ subjective estimates of the sensor errors that deviate from the actual bearing errors. These subjective estimates impact both the data association and state estimation procedures.

This mechanism enables one to test hypotheses concerning the effects of uncalibrated probabilistic judgments, where calibration is defined to be the degree to which probability judgments match empirical relative frequencies (Lichtenstein et al., 1982). Lichtenstein et al. (1982) observe that humans are poorly calibrated. In the context of this report, the ASWC is typically

furnished with a prediction of the expected bearing error $\sigma_{\varepsilon j}$ and expected detection range for a passive sensor j. These predictions are made on the basis of the state of the ocean by surface ship software packages. In the model these predictions are error-free. The ASWC's subjective estimate of the expected bearing error standard deviation is denoted $\hat{\sigma}_{\varepsilon j}$. Thus a perfectly calibrated ASWC would employ these predictions for situation assessment, i.e., $\hat{\sigma}_{\varepsilon j} = \sigma_{\varepsilon j} \overset{\Delta}{=} \sqrt{d\hat{\theta}^2}$. An imperfectly calibrated ASWC might subjectively overestimate the sensor bearing errors when the predicted bearing errors are very small and underestimate predicted bearing errors that are quite large. This calibration curve is shown in Fig. 4-7. A perfectly calibrated ASWC would have the diagonal as his calibration curve.

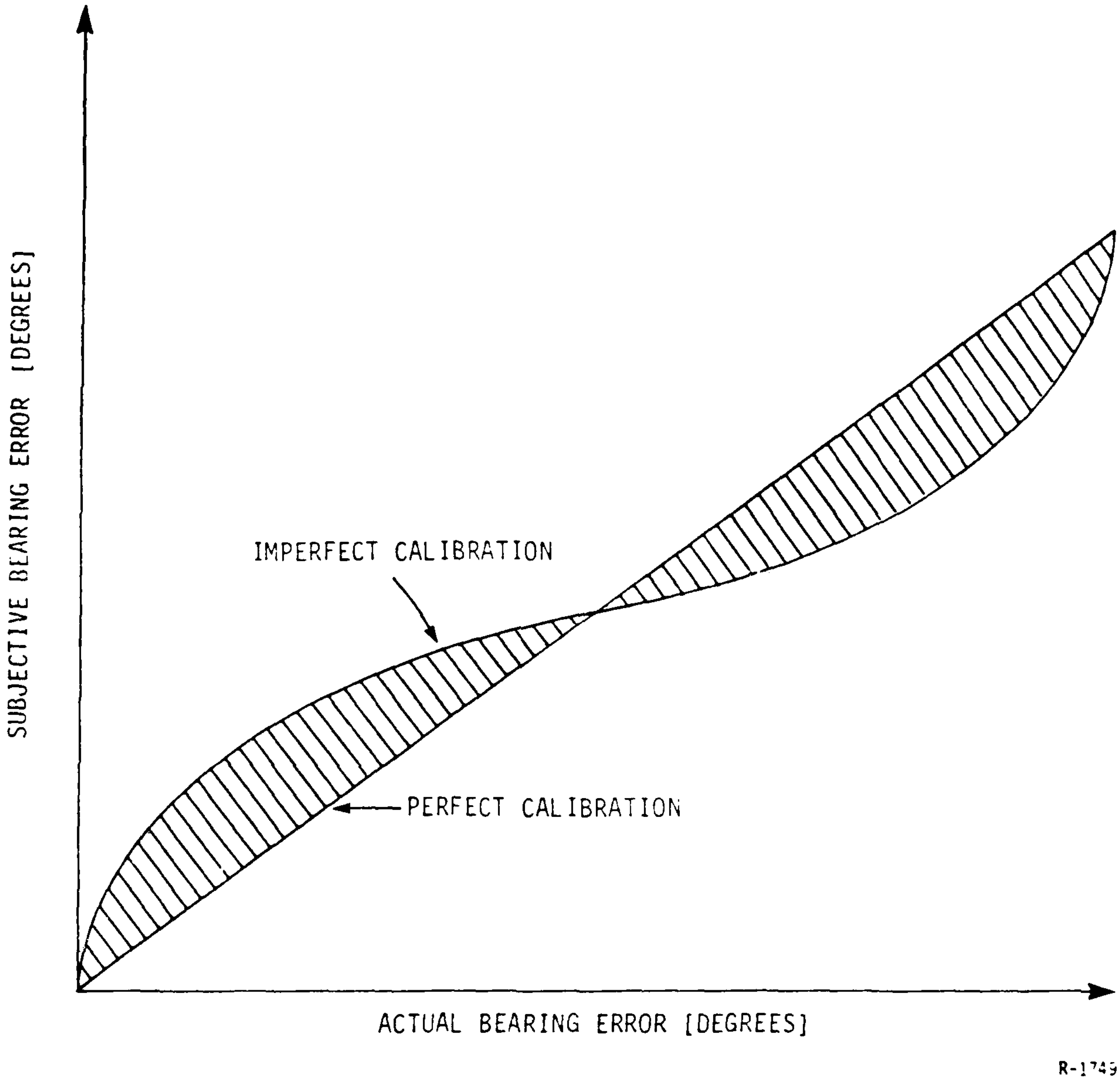


Figure 4-7. Typical ASWC Bearing Error Calibration Curve

4.4 RESOURCE MANAGER

The decision model for allocating aircraft (rotary- or fixed-wing) to pursue and to localize enemy submarines is static and event based. An aircraft mission assignment is made only subsequent to a sonar contact. The decisions are made solely on the basis of the estimated states and estimation error covariances of the tracks in the set Ω, and own-force states.

The formulation does not permit any dynamic concerns such as the retention of an asset at the current time for use in the future when its utility might be greater. Although the ASWC always considers withholding assets under moderately threatening conditions, so as not to fatigue the air crews and to ensure that an asset is available when the threat is more imminent, this concern is embedded in the cost function of a static decision problem.

4.4.1 Decision Model

In the ASW air asset assignment problem, the decisions an ASWC must make are, hierarchically:

1. The sonobuoy maneuver the asset is to use to prosecute a contact or to localize a track.
2. The asset to perform the maneuver.
3. The destination of the asset.
4. The spacing and orientation of the sonobuoys.

The ASW decision space U is a Cartesian product of sets

$$U = (M, A_i, PX, PY, W, TL) ,$$

where $w \epsilon W = [0,\infty)$, represents the sonobuoy spacing [nm] aircraft $a_i \epsilon A$ is to employ on maneuver $m \epsilon M$ at destination (px,py) in $t\ell \epsilon TL$ hours.

The decision procedure for determining which sonobuoy maneuver the asset is to employ is completely rule based. In the military, these decision rules are termed standard operating policies or doctrine. The procedures for making the remaining decisions are couched in the statistical decision theory (De-Groot, 1970) and the search and the detection theories (U.S. Naval Academy, 1977).

Sonobuoy maneuver decisions. In the model an aircraft can perform three distinct sonobuoy maneuvers: (1) a line-of-bearing (LOB) maneuver, (2) a brushtac (BT) maneuver, and (3) an entrapment (ENT) maneuver. The number of sonobuoys deployed for a maneuver are fixed. The line-of-bearing and entrap-ment procedures require eight sonobuoys each. The brushtac procedure requires sixteen sonobuoys.

The LOB maneuver is used to pursue sonar contacts and not tracks. It is the maneuver that is used when the criteria for the BT and ENT maneuvers are not satisfied. It is the least likely maneuver to redetect a submarine. An LOB consists of a line of eight sonobuoys. This line is placed along the contact bearing, or at a location and orientation that accounts for ex-pected submarine motion during the aircraft's time-late to datum. The line extends from the direct path range to the maximum passive sonar detection range. In the latter case, the ASWC assumes a submarine heading, since bearings-only contacts render no such information. The ASWC applies the con-servative rule that the submarine is acting with perfect knowledge about the battle group's plans. He, therefore, assumes that the submarine is proceeding along the course that minimizes its time to some weapons release range r_W to the carrier. The details of these calculations are discussed later in the subsection. The geometry of an LOB maneuver is depicted in Fig. 4-8.

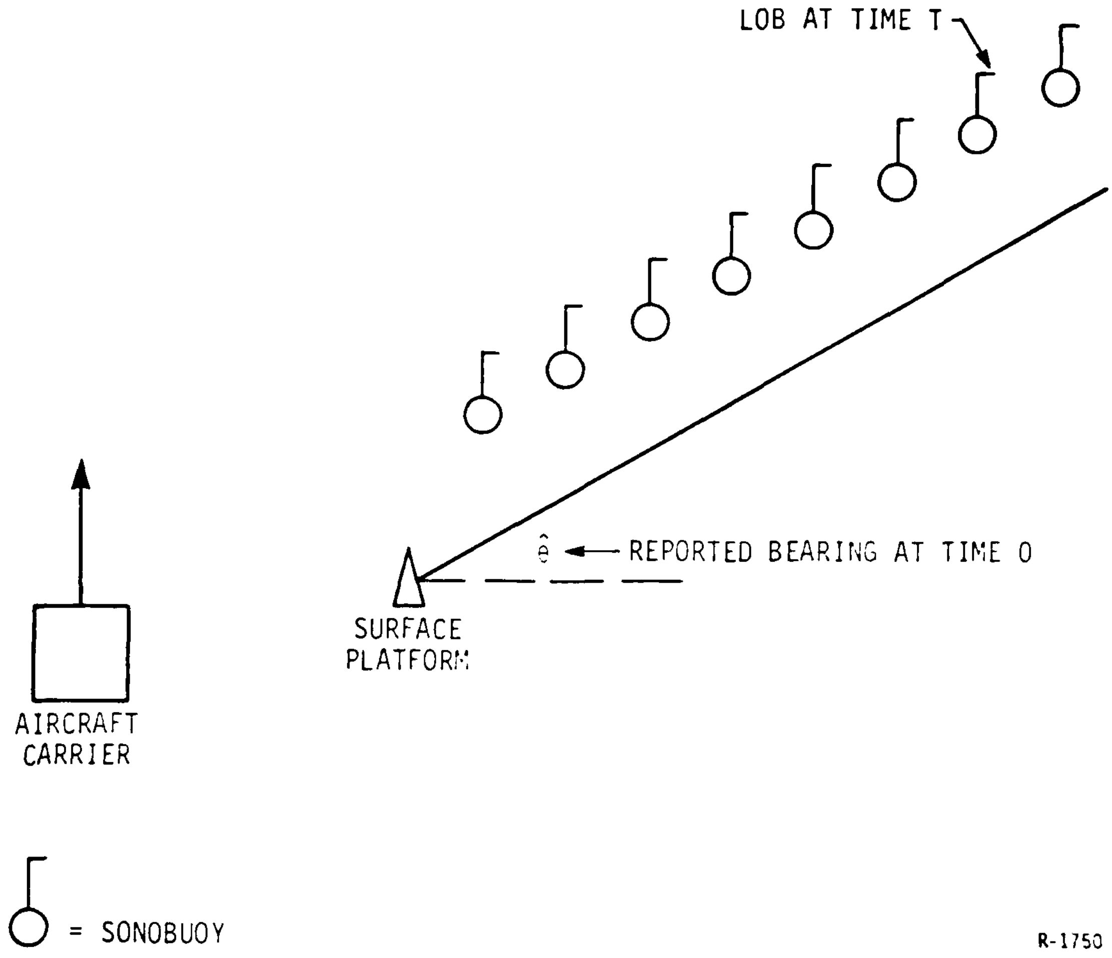


Figure 4-8. Geometry of a Line of Bearing Maneuver

The BT maneuver is employed when the ASWC has more accurate knowledge of the submarine's location. The accuracy measure is the area α of the uncertainty ellipse centered about the state estimate of the submarine's location. A BT maneuver is performed on track i if α is below an areal threshold α^*. The maneuver consists of three barriers placed perpendicular to the presumed heading of the submarine. The heading is determined using the same heuristic as in the LOB maneuver since the filter's velocity estimates are not reliable. The geometry of a BT maneuver is shown in Fig. 4-9.

When a contact is obtained from a sonobuoy, the ENT maneuver is generally used for localization. Sonobuoys provide precise position estimates on submarines that have been previously tracked because their bearing estimates are accurate and their detection ranges are, under most environmental conditions, limited to the range of the direct path. The ENT maneuver is not used subsequent to a sonobuoy contact when the aircraft's time-late-to-datum is so great that the probability of redetecting the submarine with this maneuver is negligible. In these circumstances, the BT maneuver is used. The geometry of an ENT maneuver is shown in Fig. 4-10.

A maneuver is performed for each sonar contact except when an asset is currently performing the identical, or a more precise (LOB is the least precise, ENT is the most precise) maneuver for the same track or contact in virtually the same area. Redundant maneuvers are forbidden. For instance, suppose that an aircraft had been dispatched to perform an ENT maneuver on track j at time t. If a contact (from a surface platform or sonobuoy) had been associated to track j at time $t+\Delta t$, then a strict application of the rule would require that an asset perform an LOB, a BT, or an ENT maneuver. This decision would be impractical and wasteful if the destinations of the two assets overlapped. A rational commander would realize the redundancy and not send the second asset.

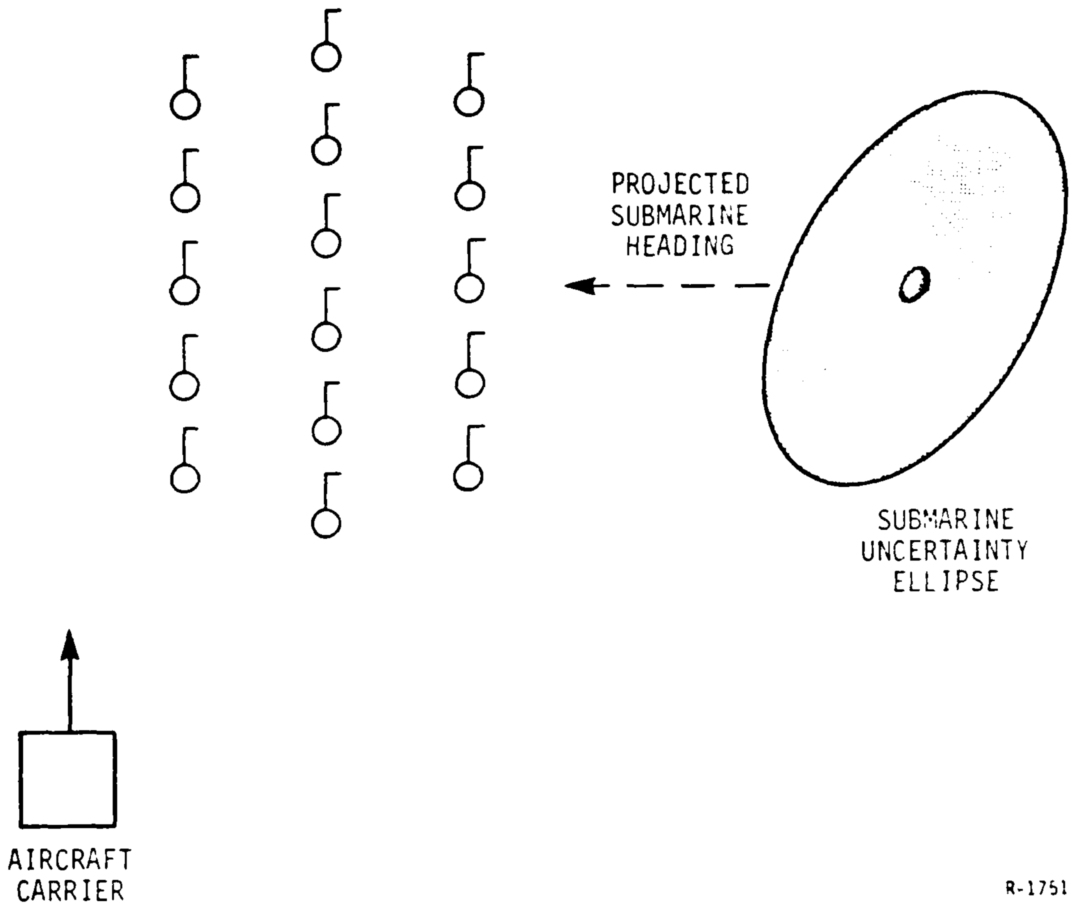


Figure 4-9. Geometry of a Brushtac Maneuver

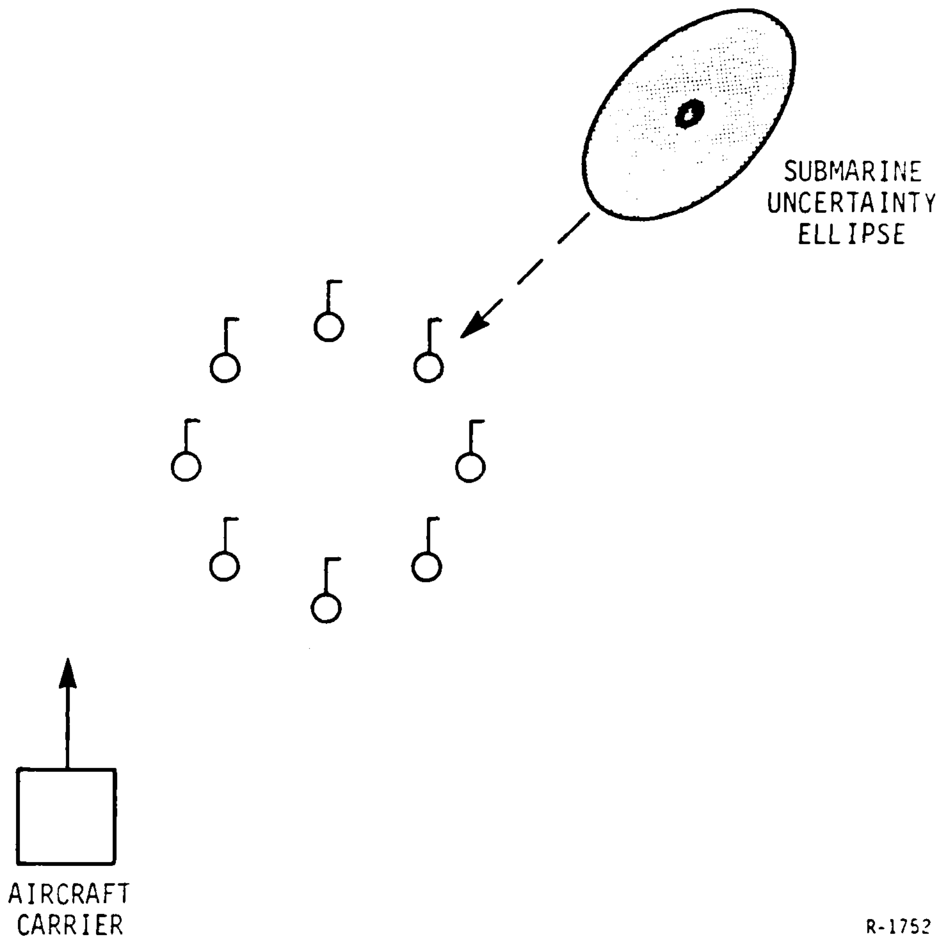


Figure 4-10. Geometry of an Entrapment Maneuver

The ASWC's three remaining decisions can not be made independently; they are clearly interconnected. The decision procedure used to select the aircraft, its destination, and the sonobuoy maneuver pattern parameters is described below.

Decision procedure. Formally, the optimal aircraft a^* for the maneuver m is determined by

$$a^* = \underset{a_i \varepsilon A}{\arg\min} \; c(a_i|m) \left(1-pd(a_i|m)\right),$$

where $c(a_i|m)$ is the cost of using aircraft a_i on maneuver m and $pd(a_i|m)$ is the probability of detecting the submarine using aircraft a_i on maneuver m. This objective function represents the tradeoffs implied by the statement: Use the least capable asset that can get the job done. Valuable aircraft, those already on missions, have a much higher cost $c(\cdot|m)$ than those residing on the decks of the carrier and surface platforms. However, the airborne aircraft usually have much higher probabilities of detection $pd(\cdot|m)$, since they can transit to the track datum more rapidly than aircraft that must be launched from the surface platforms.

Cost function $c(\cdot|m)$. The cost of using an aircraft a_i to perform maneuver m is the sum of two costs,

$$c(a_i|m) = c_1(a_i|m) + c_2(a_i|m).$$

$c_1(\cdot|m)$ is the cost associated with the amount of time an aircraft can monitor sonobuoys, i.e., the aircraft's time-on-station tos. $c_2(\cdot|m)$ is the cost associated with the number of sonobuoys N_b aboard the aircraft currently. Intuitively, aircraft that have little flight time available for sonobuoy

monitoring or few sonobuoys are not tactically useful; thus, they are assigned a high cost. And aircraft with high costs are unattractive assets given the aforementioned decision procedure.

An estimate of aircraft a_i's time-on-station tos_i for maneuver m is

$$tos_i = te_i - (t\ell_i(m) + tr_i),$$

where tr_i is the return flight time [hr] from the mission destination to a_i's mother ship. te_i and $t\ell_i(\cdot)$ are defined in subsection 4.2.1. The algorithm for computing $t\ell_i(\cdot)$ is detailed in Appendix A. For each maneuver, the $c_1(a_i|m)$ is

$$c_1(a_i|m) = \begin{cases} c_{max} & \text{if} \quad tos < t_m \,, \\ c_{max} \; 2 - \dfrac{tos}{t_m} & \text{if} \quad t_m \leq tos < 2t_m \,, \\ 0 & \text{otherwise.} \end{cases}$$

t_m is the minimum time necessary to perform a maneuver [hr] and c_{max} is the maximum cost that an aircraft can be assessed. Typically, t_{ENT} is chosen less than t_{LOB} or t_{BT} since it is often desirable to reassign aircraft on LOB or BT missions to perform ENT missions.

The second element of the cost also severely penalizes aircraft sent on LOB or BT maneuvers without an excess of sonobuoys. For LOB, BT, and ENT maneuvers, $c_2(\cdot|m)$ are:

$$c_2(a_i|m=\text{LOB}) = \begin{cases} c_{max} & \text{if} \quad N_{bi}<8 \ , \\ c_{max}/2 & \text{if} \quad 8 \leq N_{bi}<16 \ , \\ c_{max}/4 & \text{if} \quad 16 \leq N_{bi}<24 \ , \\ 0 & \text{otherwise} \ . \end{cases}$$

$$c_2(a_i|m=\text{BT}) = \begin{cases} c_{max} & \text{if} \quad N_{bi}<16 \ , \\ c_{max}/2 & \text{if} \quad 16 \leq N_{bi}<24 \ , \\ cmax/4 & \text{if} \quad 24 \leq N_{bi}<32 \ , \\ 0 & \text{otherwise} \ . \end{cases}$$

$$c_2(a_i|m=\text{ENT}) = \begin{cases} c_{max} & \text{if} \quad N_{bi}<8 \ , \\ c_{max}/4 & \text{if} \quad 8 \leq N_{bi}<16 \ , \\ 0 & \text{otherwise} \ . \end{cases}$$

The total cost $c(\cdot|m)$ must lie in the interval $[0, 2c_{max}]$. The structure of the cost function clearly favors aircraft that are not airborne since they have more flight time available and are stocked with a full inventory of sonobuoys.

Mission detection probability $pd(\cdot|m)$. The computation of the probability of detection for a sonobuoy maneuver is a function of: (1) the sonobuoy detection characteristics (the graph of the probability of sonobuoy detection versus range), (2) the geometry of the sonobuoy pattern, (3) the uncertainty in the state estimates of the submarine track, and (4) the time-late-to-datum. The detection probability estimates serve, in most cases, as upper bounds since the detection algorithm assumes idealized conditions.

$pd(\cdot|m=LOB)$ is strictly zero. The uncertainty associated with a bearings-only contact is too great to have a non-zero expectation. The primary purpose of LOB maneuvers is not to prosecute or to localize contacts, but to have aircraft airborne for more expeditious prosecution of confirmed submarine tracks.

The probabilities of detection for both the BT and ENT maneuvers are calculated using standard search and detection techniques. In particular, both maneuvers can be conceptualized as parallel-sweep search problems (U.S. Naval Academy, 1977). The parallel sweep can consist of a number of stationary sensors placed as a barrier perpendicular to the heading of the target or as a number of observers dynamically searching parallel areas. The generic formulation of the probability of detection pb for an individual, arbitrary sonobuoy barrier is described in Appendix B. Given pb, the probability of detection given a BT maneuver is

$$pd(\cdot|m=BT) = 1 - (1-pb)^3 ,$$

since the BT maneuver is comprised of three parallel barriers. The ENT maneuver is approximated as a single three-sonobuoy barrier, thus

$$pd(\cdot|m=ENT) = pb .$$

The length-of-approach (loa) of a submarine or track i is determined by the magnitude of the position state estimation errors P_i',

$$P_i' = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} ,$$

where P_{11} is the variance of the x-position estimate $\hat{px}_i$ [nm^2], P_{22} is the variance of the y-position estimate $\hat{py}_i$ [nm^2], and $P_{12}=P_{21}$ is the co-variance of the two position estimates [nm^2]. The semi-major axes of the one standard deviation uncertainty ellipse about the point $(\hat{px}_i, \hat{py}_i)$ are given by the eigenvalues $(\lambda_i^1, \lambda_i^2)$ of the matrix P_i'. The area of the ellipse α_i is

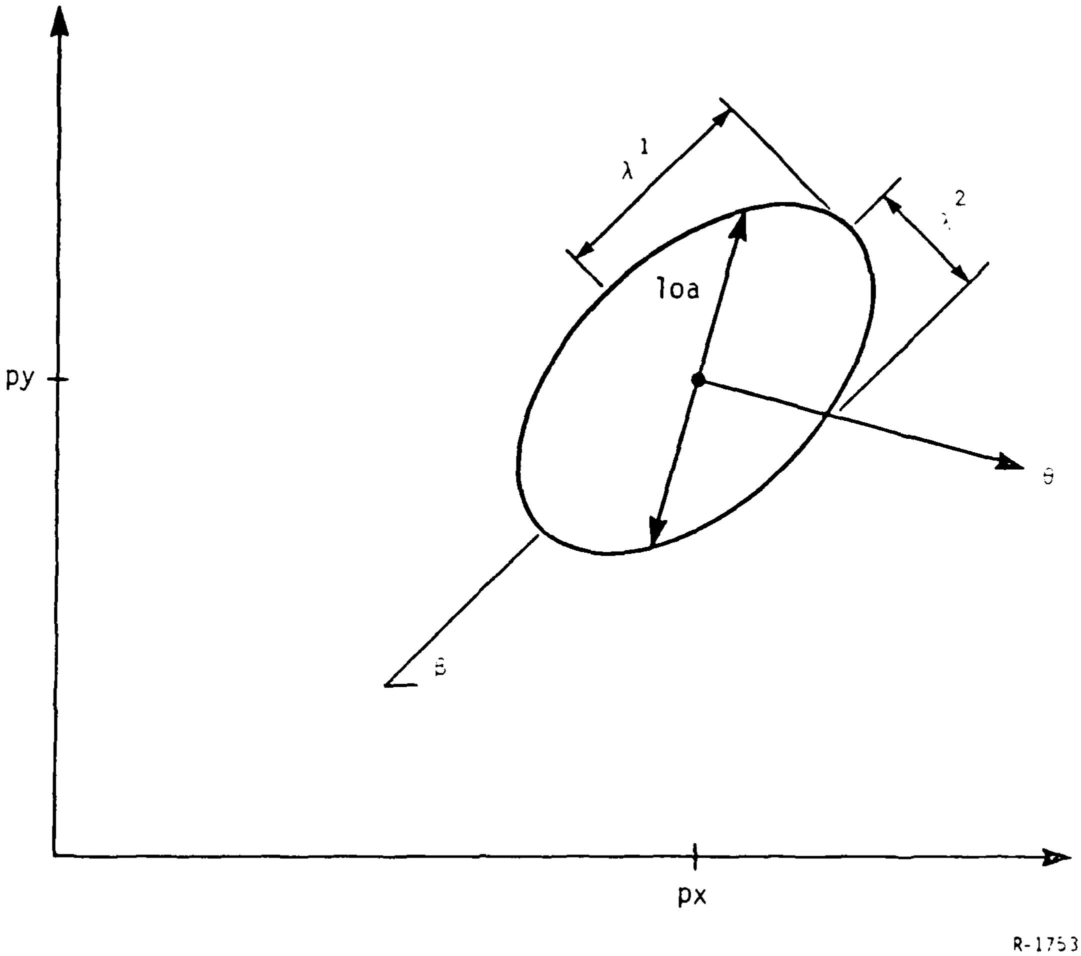
$$\alpha_i = \pi \lambda_i^1 \lambda_i^2 .$$

The orientation of the ellipse, β_i [radians], in the space PX × PY is determined by the eigenvector of P_i' (Schweppe, 1973). loa_i is defined to be the width of the ellipse perpendicular to the expected heading θ_i of the track as shown in Fig. 4-11. Thus, $loa_i \geq 2\lambda_i^2$ and $loa_i \leq 2\lambda_i^1$. For any particular ellipse orientation β_i and heading θ_i, define

$$\xi_i = \begin{cases} |\beta_i - \theta_i| - 2\pi & \text{if } 2\pi < |\beta_i - \theta_i| \;, \\ |\beta_i - \theta_i| - \pi & \text{if } \pi < |\beta_i - \theta_i| < 2\pi \;, \\ |\beta_i - \theta_i| & \text{otherwise.} \end{cases}$$

loa_i is approximated by

$$loa_i = \begin{cases} \dfrac{(\lambda_i^1 - \lambda_i^2)\xi_i}{\pi} + 2\lambda_i^2 & \text{if } 0 < \xi_i < \pi/2 \;, \\[2ex] \dfrac{4(\lambda_i^2 - \lambda_i^1)(\xi_i - \pi/2)}{\pi} + 2\lambda_i^1 & \text{otherwise} \;. \end{cases}$$



LEGEND:

loa = LENGTH OF APPROACH [nm]

β = ORIENTATION OF THE ELLIPSE [RADIANS]

θ = EXPECTED SUBMARINE HEADING [RADIANS]

λ^1, λ^2 = SEMI-MAJOR AXES OF THE ELLIPSE [nm]

Figure 4-11. Geometry of the Position Error Uncertainty Ellipse

In the absence of any heading information, the uncertainty ellipse can be expected to grow symmetrically over the time-late-to-datum $t\ell$. Thus, the ASWC projects the expected position of track i in the direction θ_i, and the magnitude of the semi-major axes of the uncertainty ellipse are

$$\lambda_i^1(t+t\ell) = \lambda_i^1(t) + v_i\, t\ell ,$$

$$\lambda_i^2(t+t\ell) = \lambda_i^2(t) + v_i\, t\ell ,$$

where v_i is the assumed speed of the submarine [nm/hr].

The lateral spacing of the sonobuoys in a BT maneuver is chosen so that $pd(\cdot|m=BT)$ is maximum; the vertical spacing is fixed at 1.5 times the detection range of a sonobuoy. For an LOB maneuver, the eight sonobuoys are spaced evenly over the line segment from the direct path range to the maximum passive sonar detection range czr_{max}. The eight sonobuoys in the ENT maneuver are spaced evenly about the circumference of a circle of radius equal to 0.75 times the detection range of a sonobuoy.

4.4.2 Descriptive Decision Model

Dynamic decision style is an important descriptive concern in decision environments with a high degree of psychological stress or threat. (Janis and Mann, 1977; Sage, 1981). Janis and Mann (1977, p.50) define psychological stress:

> ...as a generic term to designate unpleasant emotional states evoked by threatening environmental events or stimuli. A "stressful" event is any change in the environment that typically induces a high degree of unpleasant emotion...and affects normal patterns of information processing.

One of the functional relationships between psychological stress and decision style postulated by Janis and Mann (1977) is hypervigilance. In such a state the decision maker's

> ...memory span is reduced and his thinking becomes more simplistic in that he cannot deal conceptually with as many categories as when he is in a less aroused state.... Expecting that he will be helpless to avoid being victimized unless he acts quickly, the person in a state of hypervigilance fails to recognize all the alternatives open to him and fails to use whatever remaining time is available to evaluate adequately those alternatives of which he is aware (Janis and Mann, 1977, p.51).

Using an anti-aircraft artillery paradigm, Serfaty et al. (1983) have demonstrated experimentally that humans do, in fact, adapt their decision strategies to cope with increasing workload (i.e., time stress). In particular, the authors have found that humans process less input information and consider fewer alternatives as the workload is increased.

In the ASW domain, it is proposed that hypervigilance can be represented by ensuring that the optimality of the commander's decision procedure decays with increasing threat or stress. Threat, in this context, is defined to be a function of the proximity to the carrier of the state estimates of the tracks $\omega_i \varepsilon \Omega$ and the uncertainty in these state estimates α_i. Intuitively, tracks that are closer to the carrier are more threatening than those further away, and tracks whose state estimates are known perfectly are much less threatening than those with unreliable state estimates.

Specifically, the threat g_i imposed by track i is a weighted sum of a proximity (i.e., of the track state estimates to the carrier) component gp_i and an uncertainty component gu_i,

$$g_i = (1-q_i)\, gp_i + q_i\, gu_i \ .$$

q_i is the weight attributed to the track uncertainty, $0 \leq q_i \leq 1$. The proximity component gp_i is given by:

$$gp_i = \begin{cases} e^{-(d_{ic}-r_w)/czr_{max}} & \text{if } r_w < d_{ic} \ , \\ 1.0 & \text{otherwise} \ , \end{cases}$$

where d_{ic} is the distance between track ω_i's position estimate and the aircraft carrier [nm], r_w is the expected weapon release range of the submarine [nm], and czr_{max} is the maximum passive sonar detection range in the battle group [nm]. The uncertainty component is $gu_i = \alpha_i/\alpha^*$, where α^* is the BT maneuver threshold. The weight q_i is given by

$$q_i = \begin{cases} 0.5 & \text{if} \quad czr_{max} < d_{ic} \ , \\ 0.5 \left[\dfrac{d_{ic}-r_w}{czr_{max}-r_w} \right] & \text{if} \quad r_w < d_{ic} < czr_{max} \ , \\ 0 & \text{if} \quad d_{ic} < r_w \ . \end{cases}$$

This weighting scheme implies that the proximity component is the dominant contribution to the threat at short ranges. Note that $0 < q_i < 1$.

The total ASW threat gt is determined as follows. Let $\Omega' \subseteq \Omega$ be the set of tracks that are currently being pursued by aircraft on BT or ENT maneuvers and NH' be the number of tracks in the set. Let $\omega_i^* \epsilon \Omega'$ be the track with the greatest threat g^*,

$$g^* = \max_{\omega_i \epsilon \Omega'} \{g_i\} \ .$$

Thus, gt is defined

$$gt = g^* + \frac{1-g^*}{NH'-1} \left[\sum_{\substack{i=1 \\ \omega_i \epsilon \Omega' \\ \omega_i \neq \omega_i^*}}^{NH'} g_i \right] \ .$$

Given a measure of total system threat gt, which is here taken to be synonymous with psychological stress, one way to represent the departure from optimality of a commander's decision procedure is with a curve depicting the percent of admissible decisions γ a commander evaluates as a function of threat,

$$\gamma = 100e^{-gt/h} \quad .$$

When $h=\infty$, the commander is insensitive to threat, i.e., $\gamma=100\%$. As h approaches zero, γ approaches zero. A family of threat-sensitive curves is shown in Fig. 4-12. This formulation dovetails with Janis and Mann's (1977) statements alluding to the failure of decision makers "to recognize all the alternatives".

This descriptive element is imposed on the normative formulation by delimiting the search over all the possible aircraft $a_i \varepsilon A$ in the decision procedure. Given $\gamma=80\%$, the model of the commander randomly evaluates only 80% of the admissible aircraft $a_i \varepsilon A$ in the decision procedure (see subsection 4.4.1) and selects the a' that minimizes the cost function. Note that $c(a'|m) > c(a^*|m)$. On any one realization it is conceivable that $a'=a^*$, since a^* may not be one of the alternatives stricken from the admissible set A. Note that the degree of hypervigilance h can be specified to reflect a range of threat-sensitive decision behavior.

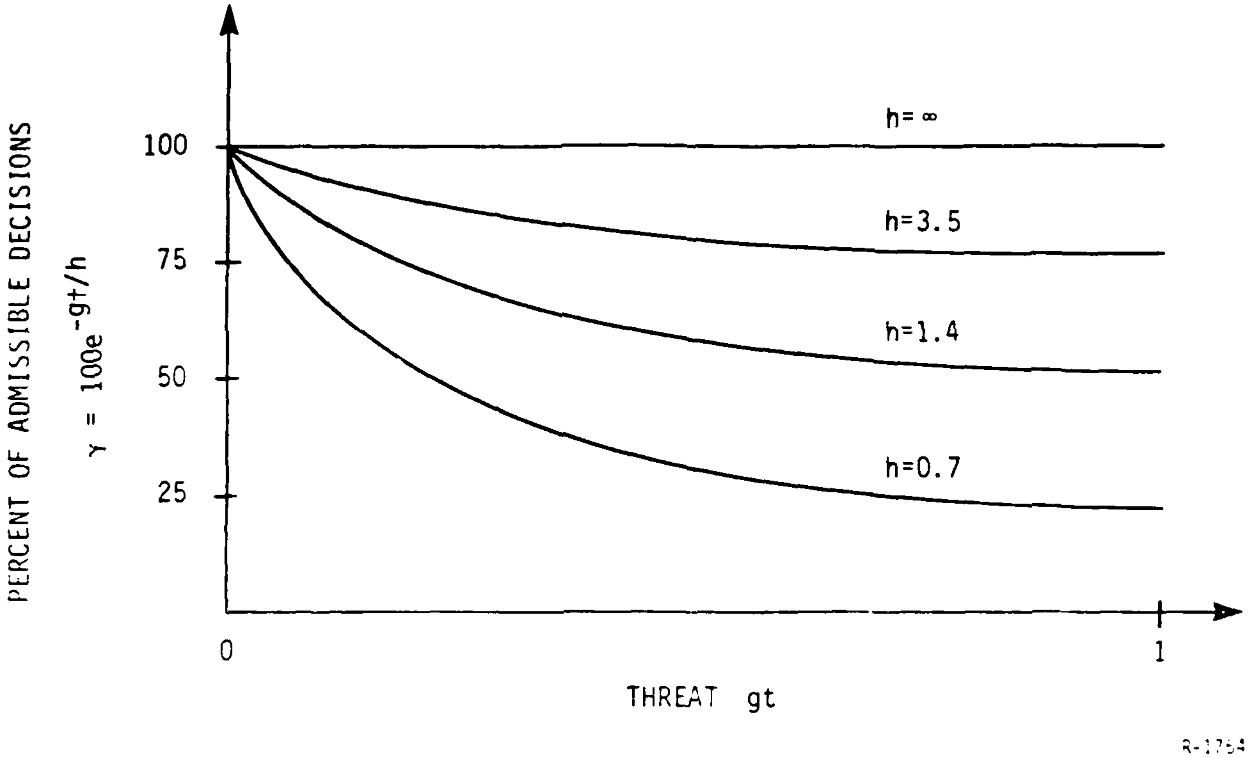


Figure 4-12. Family of Curves Describing Threat-Sensitive Decision Behavior

SECTION 5

HYPOTHETICAL CASE STUDY

In this section, the results of a hypothetical anti-submarine warfare exercise are presented. Three enemy submarines are patrolling at different areas along the battle group's line of intended motion as shown in Fig. 5-1. No active sonars are used by either the enemy submarines or the battle group platforms. Hence, the enemy submarines follow fixed trajectories, since they are unaware of any counterdetections by the battle group's platforms. The scenario terminates when: (1) an enemy submarine reaches its weapons release range to the aircraft carrier, or (2) the battle group achieves attack criterion on all three enemy submarines, or (3) the time horizon of the scenario exceeds ten hours. Attack criterion is defined to be the detection of a submarine by one of the sonobuoys in an entrapment maneuver.

The section is organized as follows. Subsection 5.1 describes the input data needed to drive the computer model. The detailed results of one realization of a specific scenario are presented in subsection 5.2. Sensitivity analyses on a subset of the descriptive and operational parameters for that scenario are given in subsection 5.3.

5.1 INPUT DATA

The purpose of this subsection is not to enumerate all the input data necessary to invoke the model, but to address only the data that serve to contribute to the understanding of the results generated by the model.

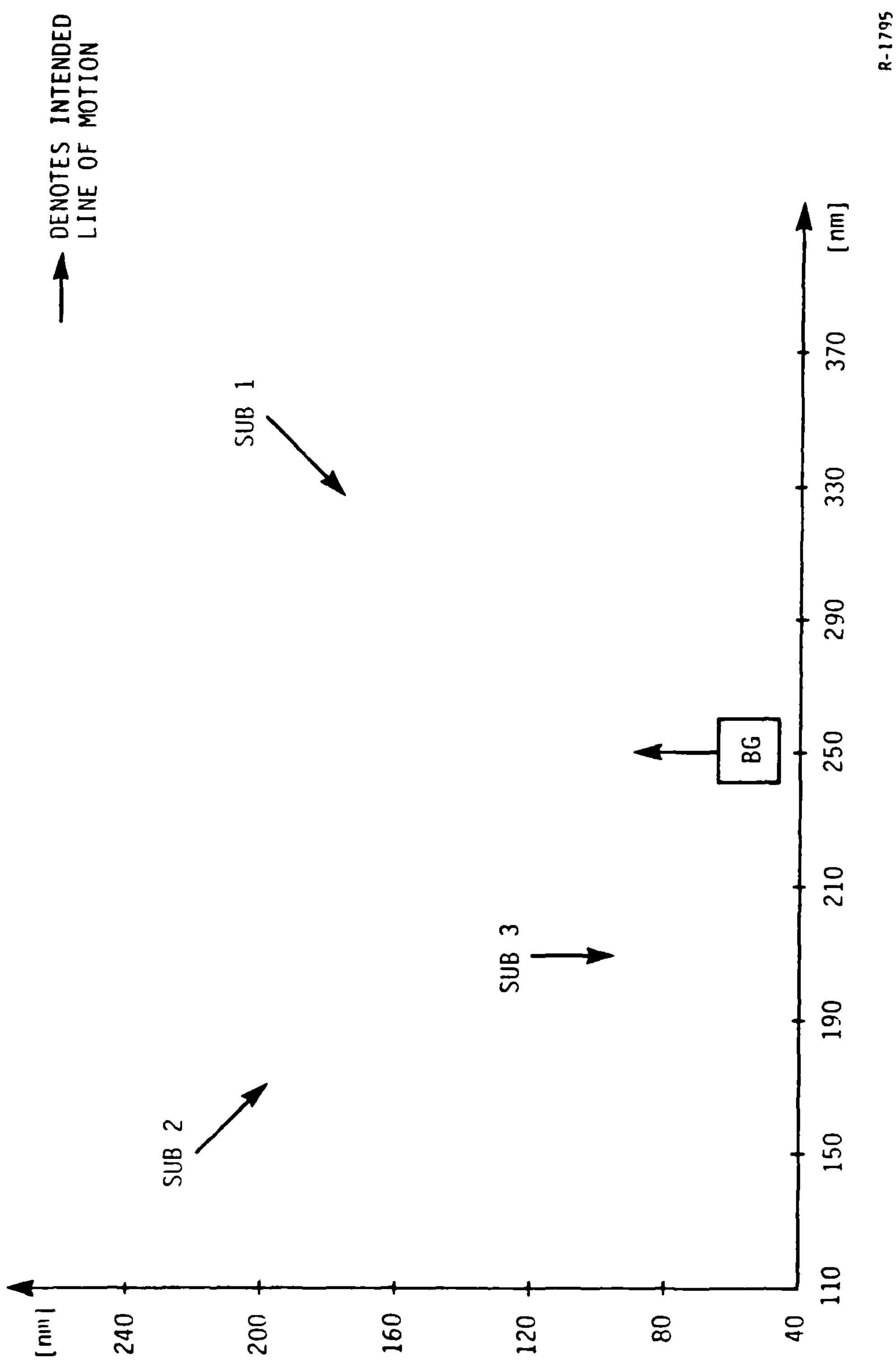


Figure 5-1. Diagram of Case Study

BG composition and disposition. The BG is comprised of one direct-support attack submarine (SSN/DS), two frigates (FF), six destroyers (DD), two cruisers (CG), and one aircraft carrier (CV). Each FF, DD, and CG carries one ASW helicopter (SH-2F). The CV embarks five SH-2F helicopters and twelve S-3A fixed-wing aircraft.

The initial disposition of the surface platforms and SSN/DS is shown in Figure 5-2. Note that the surface escorts and CV are girded by three barriers of DIFAR sonobuoys, each barrier monitored on a round-robin basis by an airborne S-3A. Another S-3A is dedicated to monitoring for a message from the SSN/DS via a SLOT buoy.

Operational characteristics. The BG speed of advance is 15 knots and its heading is due North. The CV and FFs transit at 15 knots with random headings. The FFs are, however, required to stay within fixed patrol areas about the carrier. In this way, they are ensured an average speed of 15 knots in the direction of due North. The SSN/DS patrols in a manner analogous to the DD and CG, except that it uses a sprint-and-drift cycle. A portion of its patrol time is spent operating at an optimum sonar speed of 10 knots (drifting) and the remaining time is spent operating at 25 knots, so that it can maintain the BG speed of advance. While sprinting, the SSN/DS is assumed to be incapable of passively sensing any enemy submarines.

The SH-2Fs operate at a speed of 120 knots, are equipped with 16 DIFAR sonobuoys, and can process, on board, the signals from eight sonobuoys. They require a ten minute launch delay and half-an-hour to refuel after a mission. The S-3As operate at a speed of 400 knots, are equipped with 48 DIFAR sonobuoys, and can process, on board, the signals from 24 sonobuoys. The S-3As require a 15 minute launch delay and require one hour to refuel after a mission.

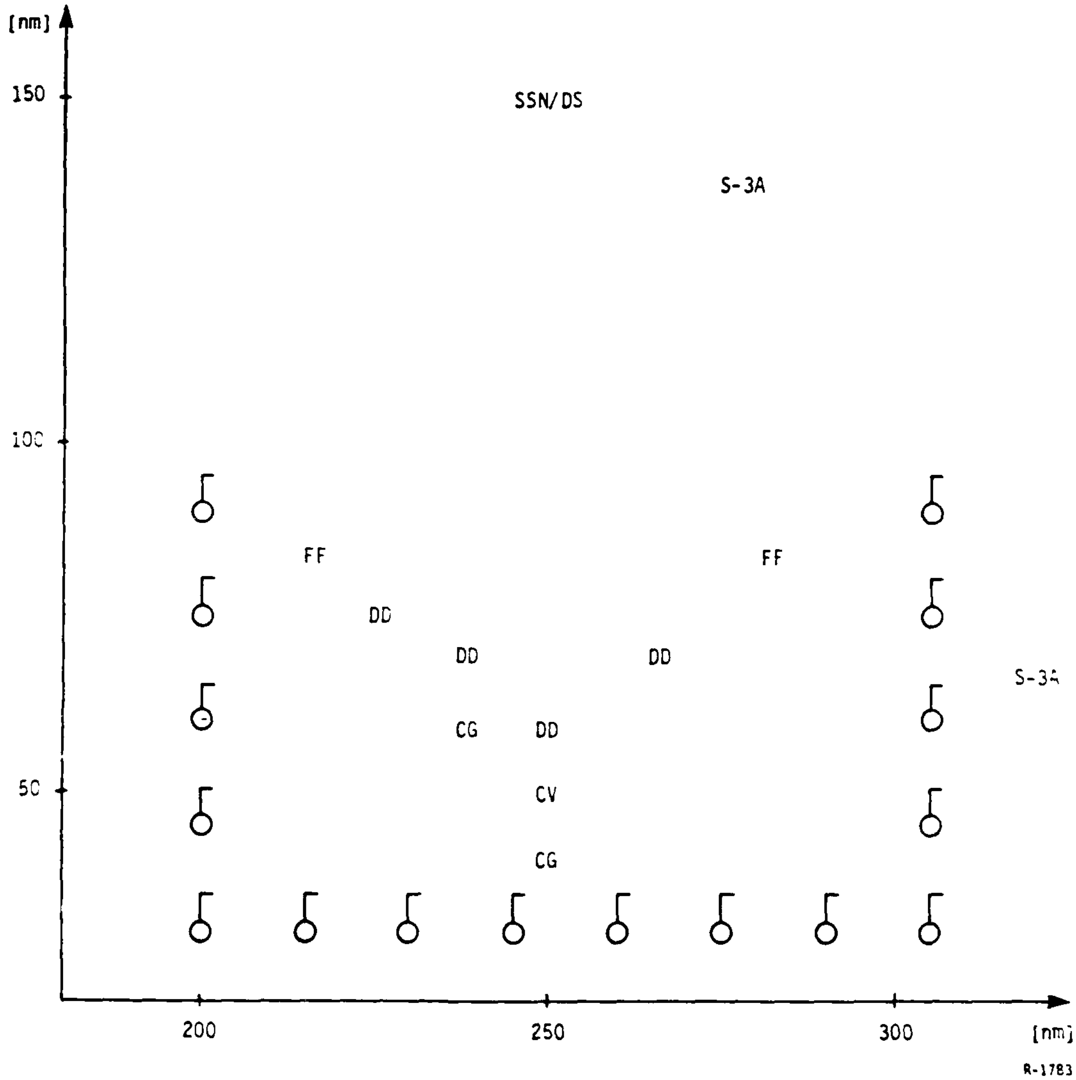


Figure 5-2. Initial Disposition of the Battle Group

The enemy submarines transit at an average speed of 15 knots with a standard deviation of 2 knots. They follow a fixed heading with a 5°/hour standard deviation. Enemy submarine and heading changes occur every two hours.

Acoustic conditions. The acoustic conditions are such that detections in the third convergence zone are possible. The direct path range czw(0) is 6 nm, the ranges to the three convergence zones czr(•) are, respectively, 30, 63, and 96 nm. The widths of all three convergence zones czw(•) are all 3 nm.

The detection characteristics for the BG platforms given this acoustic environment are summarized in Table 5-1. The detection properties of the DIFAR sonobuoys are as discussed in subsection 4.2.3. Recall that the errors in the bearings-only sonar measurements are distributed normally with a zero mean. The standard deviations σ_ε are five degrees for the FFs and for the SSN/DS, and ten degrees for the DDs, CGs, and DIFAR sonobuoys.

The values of $\hat{D}$ and $\hat{dD}$, the parameters that specify the shape of the uncertainty ellipse about a bearings-only measurement, are 60 and 50 nm, respectively.

Descriptive parameters. The number of hypotheses the ASWC can consider at any given time NH^* is seven. The ASWC's areal threshold on an uncertainty ellipse α^* is 1000 nm^2. Recall that α^* determines whether or not the ASWC can commit on air asset to a BT maneuver. The ASWC is assumed to be: (1) perfectly calibrated, (2) an optimal processor of probabilistic data, i.e., $\hat{\sigma}_\varepsilon = \sigma_\varepsilon$ for all sonar types, and (3) insensitive to threat, i.e., $h=\infty$.

The time between sonar measurements and state transitions is 0.1 hours for the simulation. The weapons release range is specified to be 30 nm for all three enemy submarines.

TABLE 5-1. DECTECTION PROBABILITIES FOR BG PLATFORMS

PLATFORM TYPE		DETECTION RANGE			
		DIRECT PATH	FIRST CZ	SECOND CZ	THIRD CZ
	SSN/DS	1.00	0.95	0.90	0.75
	FF	1.00	0.90	0.80	0.50
	DD,CG	1.00	0.70	0.50	0.00

5.2 RESULTS

The results are from one realization of a random process (detections are random). All three submarines were successfully brought to attack criterion. Submarine 3 (SUB3) was localized 3.4 hours after the onset of the simulation. SUB1 and SUB2 were localized in 4.5 and 5.8 hours after the onset of the simulation.

The histogram of sonar contact times is depicted Fig. 5-3. On the average, the time between the initial detection of a marine and the time at which the submarine was brought to attack criterion hree hours. Herein, this time is termed the time to engagement.

The discrepancy in the number of contacts on each submarine is situation specific. More than half the contacts on SUB3 were obtained from the sonobuoys on the left flank of the BG. Seven of the contacts on SUB2 in the five to six hour interval of the simulation were obtained from a BT maneuver sonobuoy that the submarine traversed.

The ASWC made thirteen distinct aircraft assignments during the scenario. Specifically, six LOB maneuvers, four BT maneuvers, and three ENT maneuvers were deployed. Only three of the LOBs, however, were actually carried out because the remaining three assignments were reassigned en route to their LOB destinations.

The maneuvers used to localize SUB3 are depicted in Fig. 5-4. SUB3 was initially detected by BG sonars at time 0.5 (note that all times refer to the elapsed simulated time in hours and the S-3As in the squadron will be termed S1,S2...). S4 was subsequently deployed to perform an LOB maneuver. At time 1.1, S4 was reassigned to perform a BT maneuver on SUB1. At time 1.3, S1 was dispatched to perform an LOB maneuver. This obviously inefficient maneuver

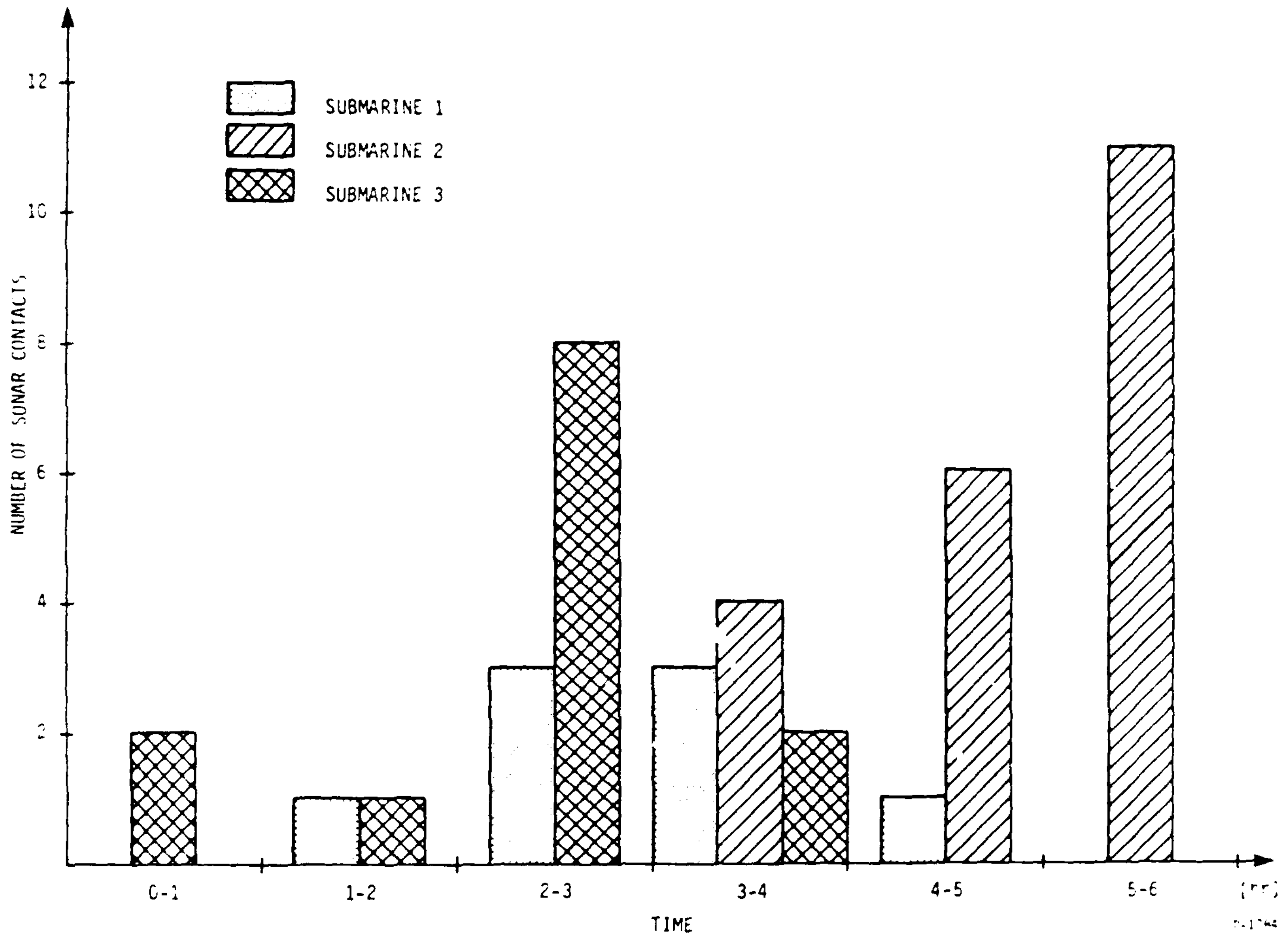


Figure 5-3. Histogram of Sonar Contact Times

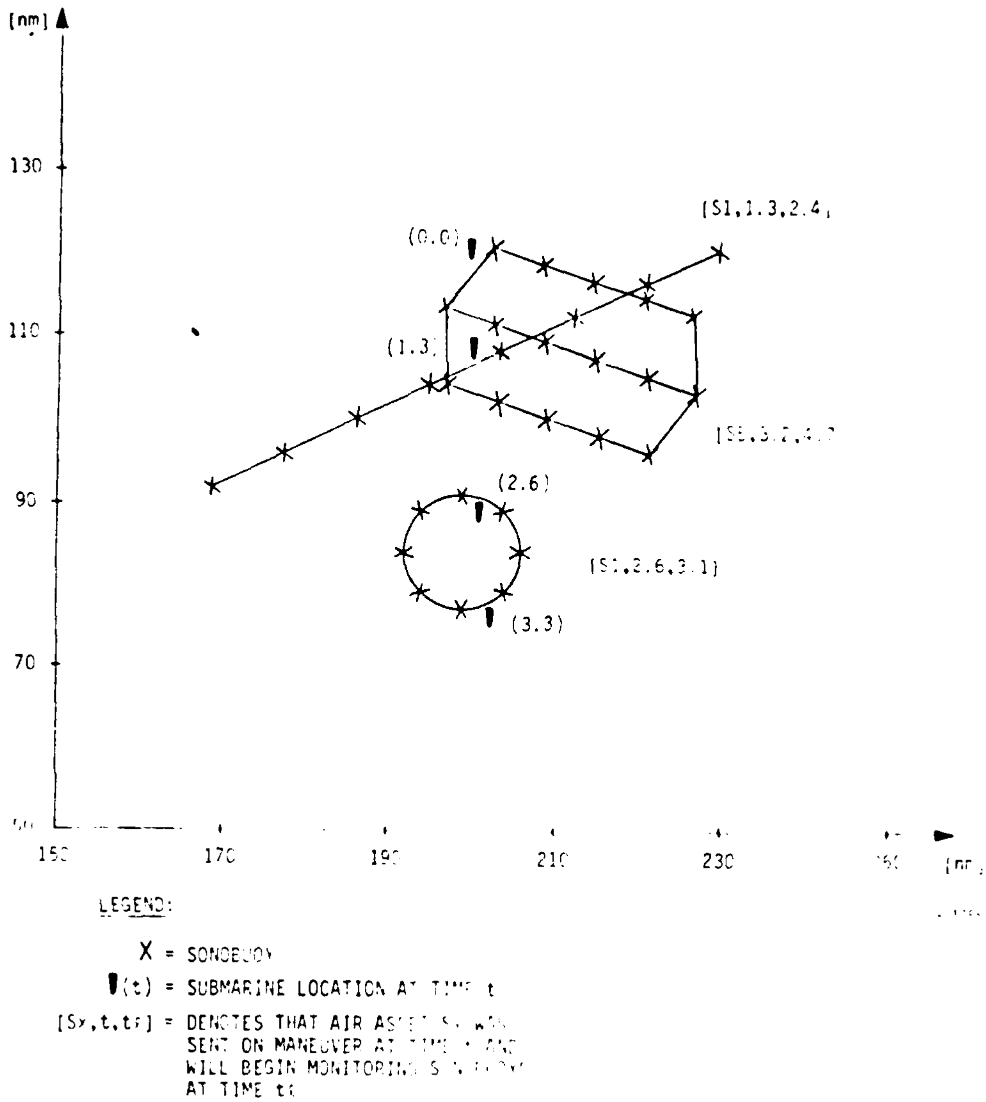


Figure 5-4. Diagram of the Maneuvers Used to Localize SUB3

was made in response to a contact from the SSN/DS. Bearings-only contacts from the SSN/DS are accurate, but are not transmitted directly to the ASWC. These data may undergo one or two hour transmission delays because: (1) there are no S-3As in the vicinity of the SSN/DS's SLOT buoy, or (2) the assigned S-3A may be monitoring the wrong channel. A sonobuoy in the barrier on the left flank of the BG (see Fig. 5-2) contacted SUB3 at time 2.6. S1 was re-assigned, then, to perform an ENT maneuver. S2 required 0.5 hours to fly to the ENT destination and lay the eight sonobuoys. Curiously, at time 3.3 S5 was dispatched from the carrier to perform a BT maneuver near SUB3. This maneuver, as opposed to an ENT, was called for because in the 0.7 hours between time 2.6 and time 3.3 no contacts on SUB3 were obtained. Thus, the ASWC's uncertainty in the sub-marine's location grew accordingly. The orientation of the BT maneuver illuminates the ASWC's assumption that the enemy submarine will take the shortest path to its weapons release range against the carrier (note that the carrier is located at roughly (250,95) at time 3.3).

Finally, at time 3.4 SUB3 was contacted by one of the sonobuoys in the ENT maneuver. Remarkably, the submarine was outside the ring of sonobuoys at this time.

Four maneuvers were required to localize SUB1 to attack criterion (see Fig. 5-5). First, a BT maneuver was performed by S4 at time 1.1. Recall that S4 was in transit to an LOB maneuver for SUB3. Clearly, this maneuver was ill-advised. It was the result of a bad association of contacts. The huge uncertainty in the location of the submarine is substantiated by the wide spacing of the sonobuoys in the maneuver.

Through time 2.2, three more contacts had been obtained on SUB1 and another BT maneuver was performed by S2. Originally, S2 was sent on an LOB

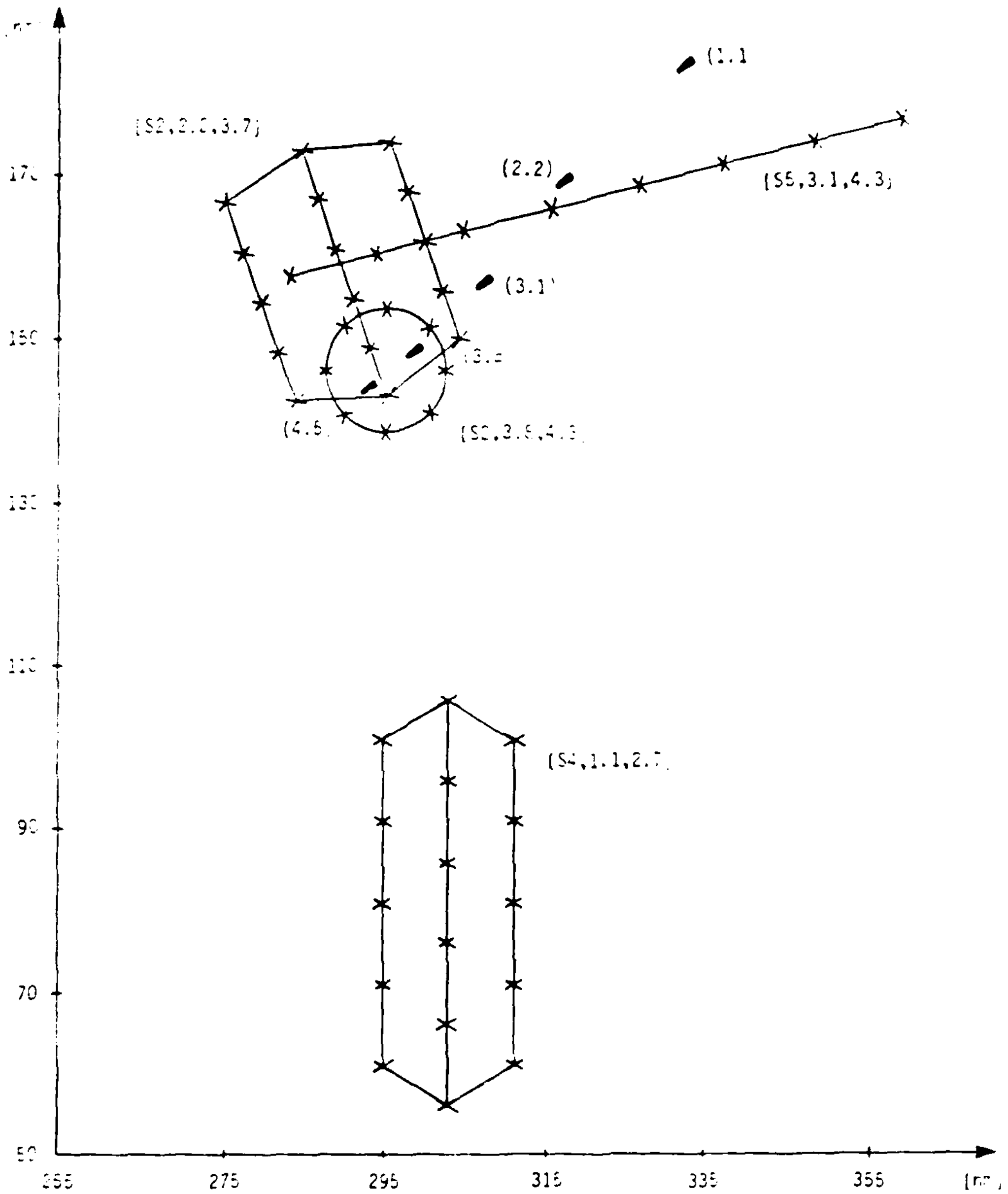


Figure 5-5. Diagram of the Maneuvers Used to Localize SUB1

maneuver at time 2.1, but was reassigned in light of the new contacts obtained at time 2.2. SUB1 was next contacted at time 3.1. Hence, S5 was ordered to perform an LOB maneuver, since the 0.9 hours of contact inactivity severely degraded the ASWC's certainty concerning the submarine's location.

SUB3 was next contacted at time 3.8 by a sonobuoy in the BT maneuver being monitored by S2. This sonobuoy contact initiated an ENT maneuver by S2 since it had the highest probability of detecting the enemy submarine, i.e., its time-late was the shortest of all the available ASW aircraft. This maneuver brought the submarine to attack criterion at time 4.5, or 0.2 hours after S2 arrived and placed the buoys in the water.

SUB2 was initially contacted by the BG sensors at time 3.1. At this time, the ASWC ordered S7 to perform an LOB maneuver as shown in Fig. 5-6. However, at the next sampling interval another platform contacted SUB2 and the ASWC was able to obtain a reasonably accurate estimate of the submarine's location, i.e., the track relating to SUB2 had a small error covariance. Thus, S7 was redeployed to perform a BT maneuver at time 3.2.

The next contact on SUB2 was obtained at time 3.8. S7 was then dispatched to perform an LOB maneuver because the ASWC's uncertainty in SUB2's location was just below α^* at time 3.2 and exceeded α^* over the 0.6 hours between contacts. Fortunately at time 4.8, SUB2 traversed the outer edge of the BT maneuver and was contacted by a sonobuoy. Note that the BT maneuver might not have been successful had not SUB2 significantly decreased its speed over the interval between 3.8 and 4.8. S6 was immediately reassigned to perform an ENT maneuver. S6 was selected in favor of S7 because S6 had a slightly higher probability of detection $pd(\cdot|m{=}ENT)$. A sonobuoy in the ENT maneuver successfully contacted SUB2 at time 5.8. If this one realization

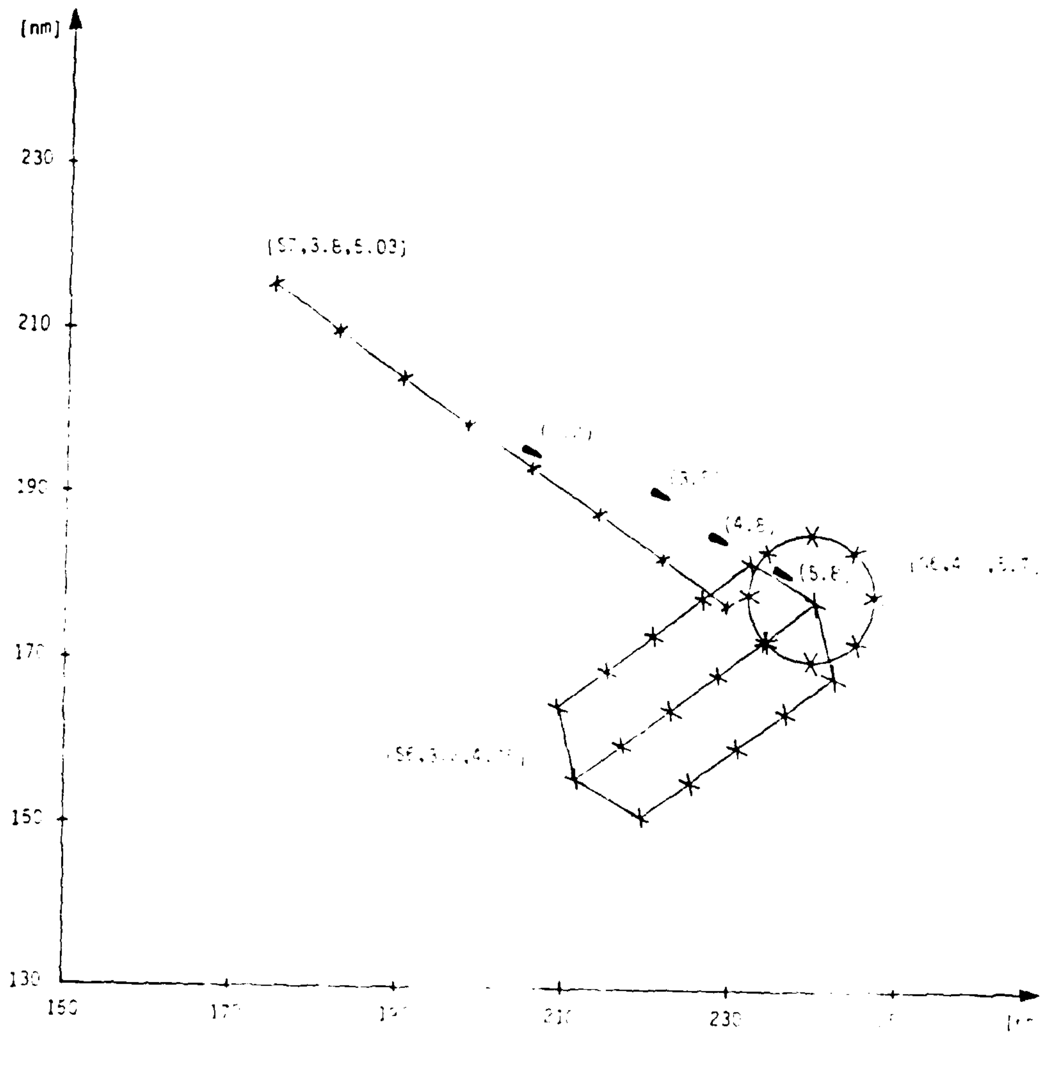


Figure 5-6. Diagram of the Maneuvers Used to Localize SUB2

of one scenario were representative of general ASW behavior, then it could be concluded that: (1) LOB maneuvers are only effective inasmuch as they get air assets aloft for reassignment, and (2) the ASW helicopters are used infrequently for the submarine localization process. The excellent results of this scenario can be attributed to the superb acoustic conditions and the small bearing errors of the sonar suites.

5.3 SENSITIVITY ANALYSES

Using the identical scenario described in the preceding subsections, sensitivity analyses on a subset of the behavioral and operational variables are presented. Two measures of system effectiveness are employed for comparison. They are: (1) the average number of submarines succcessfully brought to attack criterion NS and (2) the average time-to-engagement TE. NS represents an aggregate measure of total system effectiveness and TE is a measure that gauges the ASWC's ability to utilize his air assets effectively. The averages are computed from the results of ten independent realizations of the scenario.

Seven specific analyses are presented. The results of the analyses are depicted in Table 5-2. These results are percent changes in the two measures, NS and TE, as compared to the performance of the scenario presented in the preceding subsection (base case).

Case 1. Herein, the number of hypotheses NH^* the ASWC considers in situation assessment is restricted to three instead of the seven hypotheses used in the base case. This constraint resulted in a 4% decrease in the number of submarines engaged NS. However, the mean time-to-engagement was the same for both cases.

TABLE 5-2. RESULTS OF SENSITIVITY ANALYSIS IN COMPARISON TO BASE CASE

CASE		% CHANGE IN NS	% CHANGE IN TE
CASE	1 (THREE HYPOTHESES)	- 4.0	0.0
	2 (CALIBRATED LOW)	-57.0	+24.0
	3 (CALIBRATED HIGH)	-13.0	+ 3.0
	4 (IMPULSIVE)	-17.0	0.0
	5 (DELIBERATIVE)	-35.0	0.0
	6 (IMPROVED SONAR)	0.0	- 2.5
	7 (TWO CZ)	-32.0	-11.5

NOTATION

NS - Mean number of enemy submarines brought to attack criterion

TE - Mean time-to-engagement

Case 2. The ASWC's subjective estimates of the sonar bearing errors are miscalibrated. Specifically, the ASWC assumes that the average sonar bearing errors are one-third the actual bearing errors, i.e., 1.6° for the frigates and SSN/DS, and 3.33° for the DDs, CGs, and DIFAR sonobuoys. NS suffered a 57% decrease and TE increased by 24%. Clearly, this ignorance of the true uncertainty in the measurement errors is consequential.

Case 3. In contrast to Case 2, the ASWC's subjective estimates $\hat{\sigma}_\varepsilon$ are specified to be three times the actual sonar bearing errors σ_ε. Under these circumstances, NS was 13% less than the base case and TE was 3% greater. For this scenario, it can be concluded that it is preferable to have an ASWC that overestimates measurement error uncertainty than one who ignores it.

Case 4. In this case, the ASWC's area threshold for action α^* is increased to 2000 nm^2. This change, which has the effect of making the ASWC more impulsive, i.e., he will pursue tracks whose position estimates are known with little uncertainty, resulted in a 17% decrease in NS and TE remained the same as the base case.

Case 5. The ASWC's area threshold for action α^* is set to 500 nm^2, or one-half the value specified in the base case. If Case 4 represents impulsive decision making behavior, then this case could be construed as reflective or deliberative behavior. This threshold value caused NS to decrease by 35% as compared to the base case and TE was unaffected. Thus for this scenario, it is desirable to be impulsive rather than too deliberative.

Case 6. The sensitivity of the ASW model to an improvement in sensor bearing accuracy is examined in this case. Each sonar is assumed to have double the base case accuracy in the passive mode. That is, σ_ε is 2.5° for the FFs and SSN/DS, and 5° for the DDs, CGs, and DIFAR sonobuoys. This

improvement in the sonar measurements did not increase NS, however TE was decreased marginally by 2.5%.

Case 7. Herein, a modification in the acoustic conditions is evaluated. The FFs and SSN/DS are no longer able to obtain contacts in the third convergence zone. This inability to make long-range detections decreased NS by 32%. However, TE was also decreased by 11.5%, which is to be expected since virtually all first detections on the enemy submarines will occur at a later time and localization maneuvers will be carried out closer to the BG.

The aforementioned results are by no means conclusive. They are offered to demonstrate the wide range of model variables that could be evaluated when the model is verified completely and when more measures of total system effectiveness are developed. In addition, the sensitivity analysis results serve as partial model validation in that the model is generating results that do not conflict with intuition. For example, one would expect that a miscalibrated ASWC (Case 2 and Case 3) would not perform as effectively as one who was perfectly calibrated.

At this time, the ASWC model is capable of quantifying changes in the BG composition, BG disposition, speed of advance, platform operation parameters (maximum speeds, sonobuoy capabilities, launch delay times), sensor accuracies, acoustic conditions, the number of enemy submarines, and the cognitive characteristics of the ASWC. Thus, one can examine the relative sensitivity of total system performance to modifications in the human component, machine component, or the environmental component of the ASW system.

SECTION 6

DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 DISCUSSION

A normative-descriptive simulation model of an ASWC's tactical decision process has been developed. The decision process has been conceptualized as a cascading of two cognitive activities: situation assessment and resource allocation.

The ASWC model is driven by an environmental simulator. The environmental simulator updates the state of own-force platforms and enemy submarines and generates the submarine contacts from own-force sensors. On the basis of this information, the ASWC: (1) performs the multi-source/multi-sensor data correlation problem (situation assessment) and (2) allocates ASW aircraft for contact prosecution or target localization (resource management).

The normative representations used to describe the ASWC's cognitive activities have been drawn from the detection, estimation, and statistical decision theories. The descriptive limitations, which have been used to constrain the normative models to produce human-like behavior, have been drawn from the cognitive and behavioral literature. The limitations that have been encoded explicitly into the model are: (1) short-term memory, (2) imperfect probabilistic information processing, and (3) threat-sensitive choice making.

The model outputs the sequence of aircraft allocation decisions made by the ASWC and computes two measures of ASW system effectiveness: The number of submarines successfully brought to attack criterion and the mean time-to-engagement.

A hypothetical case study has been developed to demonstrate the model. Sensitivity analyses on both cognitive and operational parameters have been performed to illustrate the potential applications of a fully validated cognitive simulation model.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

In the next year, the research on the cognitive model of the ASWC will progress in four directions.

1. The situation assessment procedure will be modified to represent more accurately the bearings-only TMA problem under convergence zone conditions. Specifically, a bearings-only measurement will be described as n bearing/range measurements, where n is the number of convergence zones. This formulation, though more difficult to implement, is unequivocally closer to the manner the ASWC internally processes bearings-only contact data.

2. It is proposed to reformulate the resource management procedure as a dynamic decision problem under uncertainty. It is evident that the current static representation is an abstraction or simplification of the decision problem. Few ASW decisions occur in isolation; most are concerned with gathering information about the states of nature, at a cost, and many can affect the future states of nature and future decision domain. For example, when resource sources are limited, ASWCs must weigh the expected benefit of using a resource at the current time against the potential cost of not having that resource available at some future time.

The ability to explicitly capture this trade-off between present and future benefits of resource allocation decisions is the major motivation for the dynamic decision formulation. Two obvious cognitive parameters that can be incorporated are the length of the time horizon being considered and the relative weights of present and future benefits.

3. Additional measures of ASW system effectiveness will be defined. It is necessary to develop less aggregate measures than the number of submarines successfully brought to attack criterion and the mean time-to-engagement. Intermediate measures that are easily relatable to relevant system performance parameters and whose effects upon aggregate system measures could be demonstrated will be investigated.

4. Using the more realistic bearings-only formulation described above, experiments with ASW-experienced Naval personnel will be performed to assess quantitatively the validity of that normative-descriptive model of the ASWC's situation assessment procedure. Further, the effects, if any, of individual cognitive differences on ASW situation assessment will be evaluated.

While beyond the scope of next year's effort, several additional areas exist for further cognitive model research and development, particularly concerning effects of tactical intelligence data and probabilistic contact data on the ASWC's decision process.

The information provided by intelligence sources, e.g., the Sound Surveillance System (SOSUS), is known to be imperfect and is also often relayed to the BG hours after the original contact. Thus the ASWC must make two subjective probabilistic judgements that bear upon his decisionmaking. First, he must assess his degree of belief that the detection is a true detection, i.e., not a false alarm. Second, he must determine an uncertainty ellipse, or area

of uncertainty, that constitutes the target's probable location given that the detection is in fact reliable. Then, on the basis of these judgments, he is wont to revise his strategies for detecting and localizing contacts. For example, will the ASWC dispatch resources more readily? Will he pursue contacts more vigorously? Development of models that perform these tasks is increasingly relevant in view of the fact that more and more intelligence data are available to the commanders because of improved sensor and satellite technologies.

In the current model, sonar contacts are reported categorically to the ASWC. In the fleet, however, submarine contacts are conveyed to the ASWC as either a non-sub, probable-sub, or certain-sub. Moreover, the classification possible-sub is partitioned into four categories denoting the sonar operator's degree of confidence that the contact is truly a submarine. The criteria for making primary classifications are promulgated by the ASWC; the possible-sub categories are not. Note that the very fact that subjective judgements about the strength of a possible-sub contact are conveyed indicates that they must bear upon the ASWC's decisionmaking behavior. Two issues of particular interest are the procedures commanders use to transform the sonar operator's estimate into a posterior probability that a submarine is present, and the sensitivity (if any) of subsequent decision procedures to this posterior probability.

REFERENCES

Aidala, V.J. and S.E. Hammel, "Utilization of Modified Polar Coordinates for Bearings-Only Tracking," IEEE Transactions of Automatic Control, Vol. AC-28, No. 3, 1983, pp 283-294.

Atkinson, R.C. and R.M. Shiffrin, "The Control of Short-Term Memory," in Atkinson, R.L. and R.C. Atkinson (Eds.), Readings from Scientific American: Mind and Behavior, W.H. Freeman and Company, San Francisco, CA, 1980.

Bossard, D.C. and L.K. Graves, "The Theory of Screen," Daniel H. Wagner, Associates, Paoli, PA, 1980.

Crider, A.B., G.R. Goethals, R.D. Kavanaugh, and P.R. Solomon, Psychology, Scott, Foresman, and Company, Glenview, IL, 1983.

DeGroot, M.H., Optimal Statistical Decisions, McGraw-Hill, New York, 1970.

Dunnigan, J.F., How to Make War, William Morrow and Company, New York, 1982.

Einhorn, H.J., "Learning from Experience and Suboptimal Rules in Decision Making," in Wallsten, T.S. (Ed.), Cognitive Processes in Choice and Decision Behavior, Erlbaum, Hillsdale, NJ, 1980.

Einhorn, H.J. and R.M. Hogarth, "Behavioral Decision Theory: Processes of Judgment and Choice," Annual Review of Psychology, Vol. 32, 1981, pp. 53-88.

Fischhoff, B., "Hindsight Does Not Equal Foresight: The Effect of Outcome Knowledge on Judgment Under Uncertainty," Journal of Experimental Psychology: Human Perception and Performance, Vol. 1, 1975, pp. 288-299.

Gelb, A., Applied Optimal Estimation, The MIT Press, Cambridge, MA, 1974.

Hammond, K.R., "Human Judgment and Social Policy," Prog. Res. Hum. Judgment Soc. Interaction Rep. 170, University of Colorado, Boulder, CO, 1974.

Houston, J.P., B. Helen, F. Hatfield, and D.C. Rimm, Invitation to Psychology, Academic Press, New York, 1979.

Howell, W.C., "Compounding Uncertainty from Internal Sources," Journal of Experimental Psychology, Vol. 95, 1972, pp. 6-13.

Hurley, W.J., "An Introduction to the Analysis of Underwater Acoustic Detection," CRC 420, Center for Naval Analyses, Alexandria, VA, 1980.

Ivancevich, J.M. and M.T. Matteson, Stress and Work: A Managerial Perspective, Scott, Foresman, and Company, Glenview, IL, 1980.

Janis, I.L. and L. Mann, Decision Making, The Free Press, New York, 1977.

Kahneman, D. and A. Tversky, "Subjective Probability: A Judgment of Representativeness," Cognitive Psychology, Vol. 3, 1972, pp. 430-454.

Kahneman, D. and A. Tversky, "On the Psychology of Prediction," Psychological Review, Vol. 80, 1973, pp. 237-251.

Kimball, G.E. and P.M. Morse, Methods of Operations Research, Peninsula Publishing, Los Altos, CA, 1951.

Klatzky, R.L., Human Memory, W.H. Freeman and Company, San Francisco, CA, 1980.

Kleinman, D.L., S. Baron, and W.H. Levison, "A Control Theoretic Approach to Manned-Vehicle System Analysis," IEEE Transactions on Automatic Control, Vol. AC-16, No. 6, 1971, pp. 824-832.

Kleinman, D.L. and S.E. Curry, "Some New Control Theoretic Models for Human Operator Display Monitoring," IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-7, No. 11, 1977, pp. 778-784.

Lichtenstein, S., B. Fishhoff, and L. Phillips, "Calibration of Probabilities: The State of the Art to 1980," in Kahneman, D. and A. Tversky (Eds.), Judgment Under Uncertainty: Heuristics and Biases, Cambridge University Press, New York, 1982, pp. 306-334.

Loftus, G.R. and E.F. Loftus, Human Memory: The Processing of Information, Erlbaum, Hillsdale, NJ, 1976.

Lopes, L.L., "Averaging Rules and Adjustment Processes: The Role of Averaging in Inference," WHIPP 13, University of Wisconsin, Madison, WI, 1981.

Lopes, L.L., "Toward a Procedural Theory of Judgment," WHIPP 17, University of Wisconsin, Madison, WI, 1982.

Miller, G.A., "The Magical Number Seven Plus or Minus Two," Psychological Review, Vol. 63, No. 2, 1956, pp. 81-97.

Miller, D., An Illustrated Guide to Modern Submarines, AVCO Publishing, New York, 1982.

Pattipati, K.R., D.L. Kleinman, and A.R. Ephrath, "A Dynamic Decision Model of Human Task Selection Performance," IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-13, No. 3, 1983, pp. 145-166.

Payne, J.R., A.C. Miller, and J.V. Rowney, "The Naval Task Force Decision Environment," NWRC-TR-8, Stanford Research Institute, Menlo Park, CA, 1974.

Peterson, C.R., "Cascaded Inference," Organizational Behavior and Human Performance, Vol. 10, 1973, pp. 315-432.

Petridis, V.A., "A Method for Bearings-Only Velocity and Position Estimation," IEEE Transactions on Automatic Control, Vol. AC-26, No. 2, 1981, pp. 488-493.

Phillips, L.D., W.L. Hays, and W. Edwards, "Conservatism in Complex Probabilistic Inference," IEEE Transactions on Human Factors in Electronics, Vol. HFE-7, No. 1, 1966, pp. 7-18.

Rapoport, A., "Research Paradigms for Studying Dynamic Decision Behavior," in Wendt, D. and C. Vlek (Eds.), Utility, Probability, and Human Decision Making, Reidel, Dordrecht, Holland, 1975, pp. 349-369.

Rasmussen, J., "The Human as a System Component," in Smith, H. and T. Green (Eds.), Human Interaction with Computers, Academic Press, London, 1980.

Reid, D.B., "An Algorithm for Tracking Multiple Targets," IEEE Transactions on Automatic Control, Vol. AC-24, No. 6, 1979, pp. 843-852.

Rimm, D.C. and J.W. Somerville, Abnormal Psychology, Academic Press, New York, 1977.

Rouse, W.B., J.M. Hammer, and D.R. Morehead, "Modeling of Human Behavior in Seeking and Generating Information," Center for Man-Machine Systems Research, Report No. 83-1, GIT, Atlanta, GA, 1983.

Sage, A.P. and E.B. White, "Methodologies for Risk and Hazard Assessment: A Survey and Status Report," IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No. 8, 1980, pp. 425-446.

Sage, A.P., "Behavioral and Organizational Considerations in the Design of Information Systems and Processes for Planning and Decision Support," IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No. 9, 1981, pp. 640-678.

Schum, D.A., "Current Developments in Research on Cascaded Inference Processes," in Wallsten, T.S. (Ed.) Cognitive Processes in Choice and Decision Behavior, Erlbaum, Hillsdale, NJ, 1980.

Schweppe, F.C., Uncertain Dynamic Systems, Prentice-Hall, Englewood Cliffs, NJ, 1973.

Serfaty, D., E.P. Soulsby, and D.L. Kleinman, "On Human Decision Making and Information Processing Limitations in Dynamic Environments," Proceedings, Annual Conference on Manual Control, Cambridge, MA, 1983.

Sheridan, T.B. and W.R. Ferrell, Man-Machine Systems: Information, Control, and Decision Models of Human Performance, The MIT Press, Cambridge, MA, 1974.

Shuford, E.H., "Some Bayesian Learning Processes," in Shelly M.W. and G.L. Bryan (Eds.), Human Judgments and Optimality, John Wiley and Sons, New York, 1964, pp. 127-152.

Simon, H.A., Administrative Behavior, MacMillan, New York, 1957.

Simon, H.A., "On How to Decide What to Do," Bell Journal of Economics, Vol. 10, 1978, pp. 494-507.

Simon, H.A., "Rational Decision Making in Business Organizations," American Economic Review, Vol. 69, 1979, pp. 493-513.

Simon, H.A., The Sciences of the Artificial, The MIT Press, Cambridge, MA, 1981.

Sinaiko, H.W., "Operational Decison Aids: A Program of Applied Research for Naval Command and Control Systems," Manpower Research and Advisory Services, TR No. 5, Smithsonian Institution, Washington, D.C., 1977.

Singer R.A., R.G. Sea, and K.B. Housewright, "Derivation and Evaluation of Improved Tracking Filters for Use in Dense Multitarget Environments," IEEE Transactions on Information Theory, Vol. IT-20, No. 4, 1974, pp. 423-432.

Slovic, P. and S. Lichtenstein, "Comparison of Bayesian and Regression Approaches to the Study of Information Processing Judgment," Organizational Behavior and Human Performance, Vol. 6, 1971, pp. 649-744.

Slovic, P., B. Fischhoff, and S. Lichtenstein, "Behavioral Decision Theory," Annual Review of Psychology, Vol. 28, 1977, pp. 1-39.

Slovic, P., "Toward Understanding and Improving Decisions," in Howell, W.C. and E.A. Fleishman (Eds.), Human Performance and Productivity: Vol. 2, Information Processing and Decision Making, Erlbaum, Hillsdale, NJ, 1982, pp. 157-183.

Sternberg, S., "Memory-Scanning: Mental Processes Revealed by Reaction-Time Experiments," American Scientist, Vol. 57, 1969, pp. 421-457.

Toda, M., "The Design of a Fungus-Eater: A Model of Human Behavior in an Unsophisticated Environment," Behavioral Science, Vol. 7, 1962, pp. 164-183.

Tversky, A. and D. Kahneman, "The Belief in the Law of Small Numbers," Psychological Bulletin, Vol. 76, 1971, pp. 105-110.

Tversky, A. and D. Kahneman, "Availability as a Determinant of Frequency and Probability Judgments," Technical Report No. 12, Oregon Research Institute, Eugene, OR, 1972.

Tversky, A. and D. Kahneman, "Availability: A Heuristic for Judging Frequency and Probability," Cognitive Psychology, Vol. 5, 1973, pp. 207-232.

Tversky, A. and D. Kahneman, "Judgment Under Uncertainty: Heuristics and Biases," Science, Vol. 185, 1974, pp. 1124-1131.

Tversky, A. and D. Kahneman, "Extensional vs. Intuitive Reasoning: The Conjunction Fallacy in Probability Judgment," Psychological Review, forthcoming, 1984.

Urich, R.J., Principles of Underwater Sound, McGraw-Hill, New York, 1975.

U.S. Naval Academy, Naval Operations Analysis, U.S. Naval Institute, Annapolis, MD, 1977.

Van Trees, H.L., Detection, Estimation, and Modulation Theory, Part 1: Detection, Estimation, and Linear Modulation Theory, John Wiley and Sons, New York, 1968.

Wilhoit, G.Z., "Stochastic Control of a Passive Search for Ocean Vehicles," Laboratory for Information and Decision Systems, LIDS-TH-1315, MIT, Cambridge, MA, 1983.

Wohl, J.G., "Force Management Requirements for Air Force Tactical Command and Control," IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No. 9, 1981, pp. 618-639.

Wohl, J.G., E.E. Entin, and J.S. Eterno, "Modeling Human Decision Processes in Command and Control," TR-137, ALPHATECH, Inc., Burlington, MA, 1983.

Wymore, A.W., A Mathematical Theory of Systems Engineering, John Wiley and Sons, New York, 1967.

APPENDIX A

TIME-LATE CALCULATIONS

Aircraft a_i's time-late to perform sonobuoy maneuver m is

$$t\ell_i(m) = t1_i + t2_i(m) + t3_i(m),$$

where $t1_i$ is the time it requires to launch aircraft a_i [hr], $t2_i(m)$ is the time required to place the sonobuoys in the water [hr], and $t3_i(m)$ is a_i's transit time from its current location to the sonobuoy maneuver [hr].

Aircraft on the decks of the surface platforms can not be launched instantaneously. The surface platforms must be turned into the wind before aircraft can be launched. Also, aircraft can not be launched and recovered by the surface platforms simultaneously. These operational considerations impose uncertain time delays into all aircraft dispatch requests. In the model, however, the launch delays are fixed. $t1_i$ is

$$t1_i = \begin{cases} 0 & \text{if } a_i \text{ is airborne,} \\ d_f & \text{if } a_i \text{ is a fixed-wing aircraft and not airborne,} \\ d_r & \text{if } a_i \text{ is a rotary-wing aircraft and not airborne.} \end{cases}$$

Usually, the fixed-wing launch delay d_f [hr] is greater than the rotary-wing launch delay d_r [hr].

In general, $t2_i(\cdot)$ is a function of the number of sonobuoys in the maneuver and the time it takes the aircraft to distribute the sonobuoys spatially.

The maneuver time for an LOB is

$$t2_i(m{=}LOB) = 8t_b + \frac{1.5\ \left(czr(nz^*) - czr\ (0)\right)}{v_i},$$

where t_b is the time required to lay one sonobuoy [hr] and nz^* is the maximum passive sonar detection range. The middle term is multiplied by 1.5 because the aircraft monitors the buoys from the center of the line segment.

The maneuver time for a BT is

$$t2_i(m{=}BT) = 16t_b + \frac{13s_\ell}{v_i}$$

where s_ℓ is the lateral spacing of the sonobuoys [nm].

The maneuver time for an ENT is

$$t2_i(m{=}ENT) = 8t_b + \frac{2\pi s_r}{v_i},$$

where s_r is the radius of the circle defined by the eight buoys [nm].

The approximate distance d_i aircraft a_i must fly to perform maneuver m is

$$d_i = \sqrt{\left[px_i(t) - \hat{px}_s\left(t+t\ell_i(m)\right)\right]^2 + \left[py_i(t) - \hat{py}_s\left(t+t\ell_i(m)\right)\right]^2},$$

where $\left(\hat{px}_s(\cdot),\hat{py}_s(\cdot)\right)$ is the estimate of the submarine's position. For all maneuvers, the estimated position of the submarine at time $t+t\ell_i(m)$ is

$$\hat{px}_s\left(t+t\ell_i(m)\right) = \hat{px}_s(t) + v_s\ t\ell_i(m)\cos\theta_s^*,$$

$$\hat{py}_s(t+t\ell_i(m)) = \hat{py}_s(t) + v_s\, t\ell_i(m) \sin \theta_s^*.$$

where θ_s^* is the assumed submarine heading discussed below. When m=LOB, the initial position of the submarine is calulated

$$\hat{px}_s(t) = px_j(t) + \hat{D} \cos \hat{\theta},$$

$$\hat{py}_s(t) = py_j(t) + \hat{D} \sin \hat{\theta},$$

where $\{px_j(\cdot), py_j(\cdot)\}$ is the position of the sensor that generated the contact and $\hat{\theta}$ is the measured bearing . $\hat{D}$ is as defined in subsection 4.3. When m=BT or m=ENT

$$\hat{px}_s(t) = px_k(t),$$
$$\hat{py}_s(t) = py_k(t),$$

where $px_k(\cdot)$ and $py_k(\cdot)$ are the position estimates of track k. The transit time $t3_i(m)$ is thereby approximated by

$$t3_i(m) = \frac{d_i}{v_i} \quad .$$

Note that the maneuver destination is the expected position of the submarine one-half-hour after the aircraft obtains its destination, places the sonobuoys in the water, and begins monitoring the sonobuoys. This destination accounts for the motion of the submarine while the aircraft is waiting to be launched, transiting, and placing buoys in the water, with a half hour arbitarily added to ensure leading the submarine. In the absense of velocity information, the ASWC is assumed to employ the worst-case hypothesis: Assume the enemy submarine is operating with perfect knowledge as to the aircraft carrier's speed of advance, v_c, and heading, θ_c. Furthermore, the ASWC

assumes that the submarine chooses a heading θ_s^* (given a fixed velocity v_s) that minimizes the time required, Δt, to transit from its current location to a range, r_w, at which it can release its weapons against the carrier. Specifically, θ_s^* is

$$\theta_s^* = \underset{\theta_s=[0,2\pi)}{\arg\min} \quad \Delta t \qquad ,$$

subject to:

$$[px_c(t) + \Delta t\ v_c \cos\theta_c - (px_s(t) + \Delta t\ v_s \cos\theta_s)]^2 +$$
$$[py_c(t) + \Delta t\ v_c \sin\theta_c - (py_s(t) + \Delta t\ v_s \sin\theta_s)]^2 \leq r_w^2 \quad .$$

APPENDIX B

PROBABILITY OF DETECTION FOR SONOBUOY BARRIERS

Given a lateral range curve p(•) (vide, subsection 4.2.3), the average probability of detection for one sonobuoy is

$$E[p(x)] = \int_{-\infty}^{\infty} p(x)\ f(x)\ dx\ ,$$

where f(•) is the probability density function of the submarine's lateral range. In submarine search, f(•) is assumed to be a uniform probability density. Let czw(0) = r and

$$p(x) = \begin{cases} e^{-0.693x/r} & 0 \leq x\ , \\ e^{0.693/r} & x < 0\ , \end{cases}$$

as specified in subsection 4.2.3. Thus $f(x) = \frac{1}{2r}$. The probability of detecting a submarine that travels r nautical miles from a sonobuoy is

$$E[p(x)] = \int_{-r}^{r} p(x)\ f(x)\ dx$$

$$= \frac{2}{2r} \int_{0}^{r} e^{-0.693x/r}\ dx\ ,$$

$$= 0.72.$$

In a sonobuoy barrier where the lateral range curves of the sonobuoys overlap (Fig. B-1), i.e., the sonobuoy spacing $s < 2r$, the probability of detecting a submarine is greater than 0.72. Thus the expected probability of detecting a submarine that passes between two sonobuoys with overlapping lateral ranges is (using the notation defined in Fig. B-1),

$$E[p(x)] = \frac{1}{s}\left[\int_0^{s-r} e^{-0.693s/r}\,dx + \int_r^{s} e^{0.693x/r}\,dx + 2\int_{s-r}^{r/2} e^{-0.693x/r}\,dx\right],$$

$$= \frac{2.89r}{s}\left[1.0 - e^{-0.693s/2.0r}\right].$$

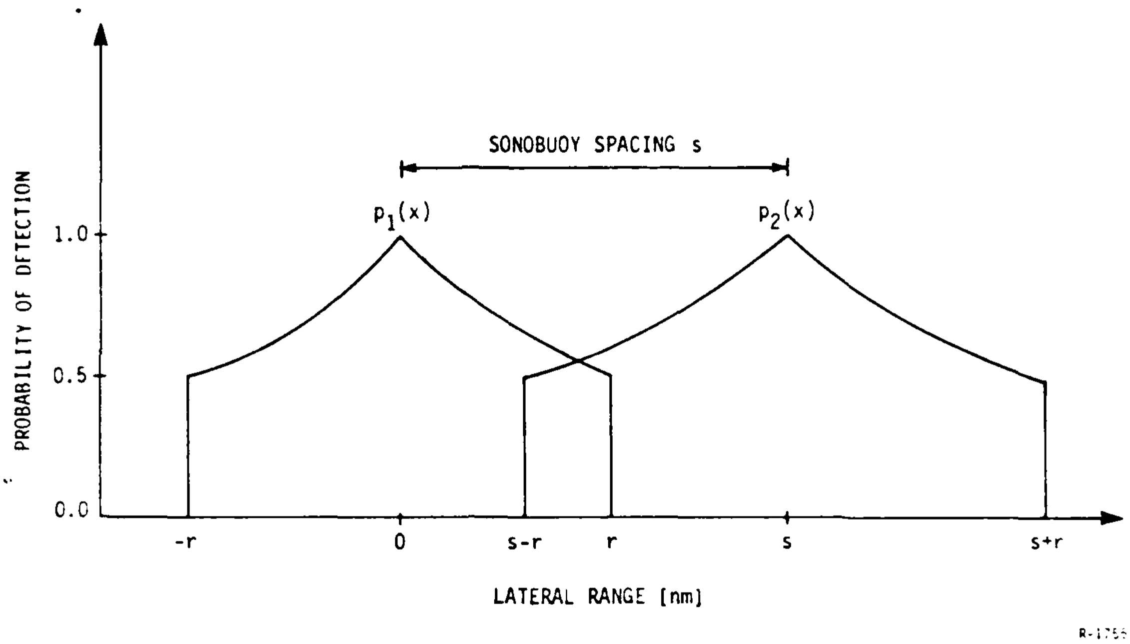
As $s \to 2r$, $E[p(x)] \to 0.72$.

The expected probability of detection for a sonobuoy barrier pb comprised of nb sonobuoys spaced at a distance s with detection range r is derived as follows. Let the extent of the barrier be defined as $(nb-1)s + 2r$. When the lateral range of the submarine, or length of approach loa, exceeds $(nb-1)s + 2r$, pb is

$$pb = \begin{cases} \dfrac{0.72\left[(nb-1)s+2r\right]}{loa} & \text{if } 2r \leq s \quad , \\[2ex] \dfrac{2.89r}{s}\left[1.0 - e^{-0.693s/2.0r}\right]\dfrac{\left[(nb-1)s+2r\right]}{loa} & \text{if } s < 2r \quad . \end{cases}$$

When $loa < (nb-1)s + 2r$, pb is simply given by

$$pb = \begin{cases} 0.72 & \text{if } 2r \leq s \quad , \\[2ex] \dfrac{2.89}{s}\left[1.0 - e^{-0.693s/2.0r}\right] & \text{if } s < 2r \quad . \end{cases}$$



LEGEND:

$p_1(\cdot)$ = LATERAL RANGE CURVE FOR SONOBUOY 1

$p_2(\cdot)$ = LATERAL RANGE CURVE FOR SONOBUOY 2

r = SONOBUOY DETECTION RANGE [nm]

s = SONOBUOY SPACING [nm]

Figure B-1. Overlapping Sonobuoy Lateral Range Curves